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THE MECHANICAL INTERPRETATION OF JOINTS

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PART II

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I. MOHR'S THEORY OF RUPTURE[1]

BY LOUIS BRAND

Let P denote a point of a body at which the state of stress is to be investigated. For this purpose imagine a sphere of infinitesimal radius described about P as center (Fig. 10); then the totality of the stresses at all the surface elements of the sphere constitute the state of stress at the point P. A surface element of the sphere may be specified by means of the vector radius to the element. The surface r thus means an infinitely small plane surface tangent to the sphere at the end of r. In the following, the stresses shown

[1] This account of Mohr's theory of rupture was written at the writer's request by Professor Louis Brand, of the University of Cincinnati, to whom he wishes herewith to express his sincere thanks.

acting upon the sphere are those due to outside matter. Since we assume that the stress distribution within the body is continuous, the stresses that correspond to the two surface elements at the end of a diameter of the sphere are therefore numerically equal and opposite in sign, except for negligibly small quantities.

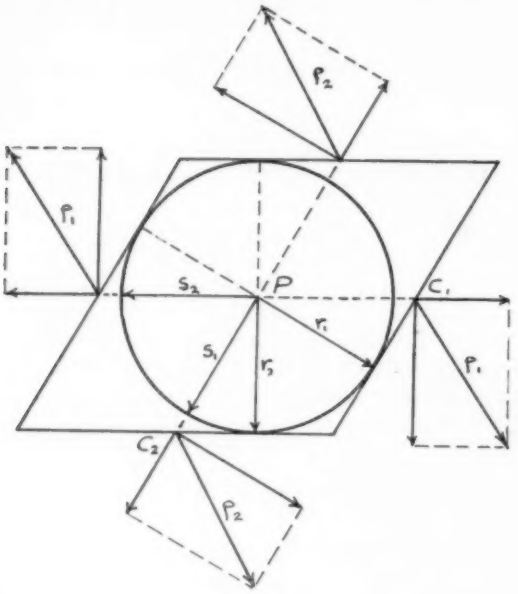

FIG. 10

We shall now obtain the relation between the unit stresses ρ_1, ρ_2 at the two surfaces r_1, r_2. Form a parallelepiped with three pairs of planes tangent to the sphere, one pair normal to r_1, another to r_2, while a third pair is normal to a radius r_3 which is perpendicular to both r_1 and r_2. Figure 10 shows the projection of this parallelepiped upon a plane through P normal to r_3. Both faces normal to r_3 project into a rhombus. The other four faces are rectangles of equal area, dA, and project into lines. Now resolve the stresses ρ_1 into three components: parallel to r_2, parallel to r_3, and normal

to r_2, r_3. Similarly resolve the stresses ρ_2 into three components: parallel to r_1, parallel to r_3, and normal to r_1, r_3. Of these components, only the first named of each set, namely,

$$\rho_1 \cos(\rho_1 r_2),\ \rho_2 \cos(\rho_2 r_1),$$

have moments about r_3. Hence for equilibrium as regards rotation about r_3, we have

$$2dA \cdot \rho_1 \cos(\rho_1 r_2) \cdot \overline{PC_1} = 2dA \cdot \rho_2 \cos(\rho_2 r_1) \cdot \overline{PC_2};$$

or, since $\overline{PC_1} = \overline{PC_2}$,

$$\rho_1 \cos(\rho_1 r_2) = \rho_2 \cos(\rho_2 r_1). \tag{1}$$

The angles indicated are those between the stresses and *outwardly directed radii*. The fundamental equation (1) may be stated as follows:

If ρ_1, ρ_2 are unit stresses at the surface elements r_1, r_2, the projection of ρ_1 upon r_2 is equal to the projection of ρ_2 upon r_1.

We proceed to put equation (1) in a more usable form. Let us regard angles in the plane of r_1, r_2 as positive when clockwise; and let s_1, s_2 denote radii in this plane 90° *ahead* of r_1, r_2 respectively. Now resolve ρ_1 into components as follows: (1) $\sigma_1 = \rho_1 \cos(\rho_1 r_1)$, parallel to r_1; (2) $\tau_1 = \rho_1 \cos(\rho_1 s_1)$, parallel to s_1; (3) parallel to r_3. Also resolve ρ_2 into the components: (1) $\sigma_2 = \rho_2 \cos(\rho_2 r_2)$, parallel to r_2; (2) $\tau_2 = \rho_2 \cos(\rho_2 s_2)$, parallel to s_2; (3) parallel to r_3. The *normal stresses* σ_1, σ_2 (i.e., normal to their surface elements) are positive when directed outward from P, or when they are *tensions*. The components τ_1, τ_2 of the *shearing stresses* are positive when they produce clockwise moments about r_3. We now transform the cosines in (1) by means of the formula for the angle between two directions in space:

$$\begin{aligned}
\cos(\rho_1 r_2) &= \cos(\rho_1 r_1)\cos(r_2 r_1) + \cos(\rho_1 s_1)\cos(r_2 s_1) + \cos(\rho_1 r_3)\cdot\cos(r_2 r_3) \\
&= \cos(\rho_1 r_1)\cos(r_1 r_2) + \cos(\rho_1 s_1)\sin(r_1 r_2), \\
\cos(\rho_2 r_1) &= \cos(\rho_2 r_2)\cos(r_1 r_2) + \cos(\rho_2 s_2)\cos(r_1 s_2) + \cos(\rho_2 r_3)\cos(r_1 r_3) \\
&= \cos(\rho_2 r_2)\cos(r_1 r_2) - \cos(\rho_2 s_2)\sin(r_1 r_2).
\end{aligned}$$

Substituting the values in (1) and noting the above values for σ_1, σ_2, τ_1, τ_2, we have

$$\sigma_1 \cos (r_1r_2)+\tau_1 \sin (r_1r_2)=\sigma_2 \cos (r_1r_2)-\tau_2 \sin (r_1r_2),$$

or

$$(\sigma_2-\sigma_1) \cos (r_1r_2)=(\tau_1+\tau_2) \sin (r_1r_2). \tag{2}$$

As a first application of this equation we have

$$\tau_1+\tau_2=0 \quad \text{when} \quad (r_1r_2)=90°. \tag{3}$$

In this case the shearing stresses are numerically equal but opposite in sign.

Next, let r_0 be any fixed radius in the plane r_1, r_2; and write

$$\phi=(r_0r_1),\ \phi+\Delta\phi=(r_0r_2);\ \ \sigma_2=\sigma_1+\Delta\sigma,\ \tau_2=\tau_1+\Delta\tau.$$

Then (2) assumes the form

$$\Delta\sigma \cos \Delta\phi=(2\tau_1+\Delta\tau) \sin \Delta\phi;$$

dividing through by $\Delta\phi$ and letting $\Delta\phi$ approach zero, we obtain

$$\frac{d\sigma}{d\phi}=2\tau, \tag{4}$$

the subscript being no longer needed. From this equation it appears that σ increases with ϕ when τ has the direction of increasing ϕ.

If σ is not constant over the sphere it must reach a minimum σ_x and a maximum σ_z at certain diameters which we denote by x and z respectively. At these points $\frac{d\sigma}{d\phi}=0$ for *all* diametral planes; hence from (4) the *total* shear vanishes at x and z. Also, from (2), $\cos (xz)=0$, so that x and z are perpendicular. Again, if y is a third diameter, perpendicular to both x and z, the components of shear in both yx and yz planes vanish by virtue of (3), and hence the *total* shear for y is also zero. The three mutually perpendicular diameters x, y, z, are called the *principal axes*, the planes xy, yz, zx, the *principal planes*, and the stresses σ_x, σ_y, σ_z, the *principal stresses*

at the point P. When the principal stresses are unequal the notation has been chosen so that $\sigma_x < \sigma_y < \sigma_z$.

We now choose positive directions on the principal axes, and denote the positive principal radii by r_x, r_y, r_z. Then, if ρ is the stress at any surface r, we have from (1)

$$\left.\begin{aligned} \rho \cos(\rho r_x) &= \sigma_x \cos(r r_x), \\ \rho \cos(\rho r_y) &= \sigma_y \cos(r r_y), \\ \rho \cos(\rho r_z) &= \sigma_z \cos(r r_z). \end{aligned}\right\} \tag{5}$$

The components of the stress at any surface r are thus given in terms of the principal stresses and the direction cosines of r. From these components we may compute the normal stress, σ, at r:

$$\sigma = \rho \cos(\rho r) = \sigma_x \cos^2(r r_x) + \sigma_y \cos^2(r r_y) + \sigma_z \cos^2(r r_z). \tag{6}$$

The equations (5) show, moreover, that the stresses over the sphere are symmetrically distributed with respect to each of the three principal planes. It is sufficient, therefore, to know the stress distribution in one of the octants into which the principal planes divide the sphere.

We shall now examine the stress distribution in the principal planes. Let r be a radius in the xz plane making an angle $\phi = (r r_z)$ with the positive z-axis. Since $(r r_y) = 90°$, we have from (5) that $(\rho r_y) = 90°$; hence the stresses in a principal plane lie entirely in that plane. From (6) we have for the normal stress at r

$$\sigma = \sigma_x \sin^2\phi + \sigma_z \cos^2\phi = \frac{\sigma_x + \sigma_z}{2} + \frac{\sigma_z - \sigma_x}{2} \cos 2\phi. \tag{7}$$

To obtain τ we put $\sigma_2 = \sigma_z$, $\tau_2 = \tau_z = 0$, $r_2 = r_z$ in (2); then, by virtue of (7),

$$\tau = (\sigma_z - \sigma) \frac{\cos\phi}{\sin\phi} = (\sigma_z - \sigma_x) \sin\phi \cos\phi = \frac{\sigma_z - \sigma_x}{2} \sin 2\phi. \tag{8}$$

If σ, τ are regarded as rectangular co-ordinates, equations (7) and (8) are the parametric equations of a circle of center $[(\sigma_x + \sigma_z)/2, 0]$ and radius $(\sigma_z - \sigma_x)/2$. We thus have the following graphical representation of the stress distribution in the xz plane: Lay off

$\overline{OX}=\sigma_x$, $\overline{OZ}=\sigma_z$ on the axis of abscissas (Fig. 11), and draw a circle having $\overline{XZ}$ as diameter. This circle has the center and radius specified above; and the abscissa and ordinate of any point R of the circle represent the normal and shearing stress, σ, τ, respectively, which correspond to a radius r of the sphere in the xz plane and making an angle ϕ with r_z equal to one-half of the central angle ZCR.

If we lay off $\overline{OY}=\sigma_y$, a similar argument shows that the stress distributions on the xy and yz planes are represented by the co-ordinates of the points forming the circles on $\overline{XY}$ and $\overline{YZ}$ as

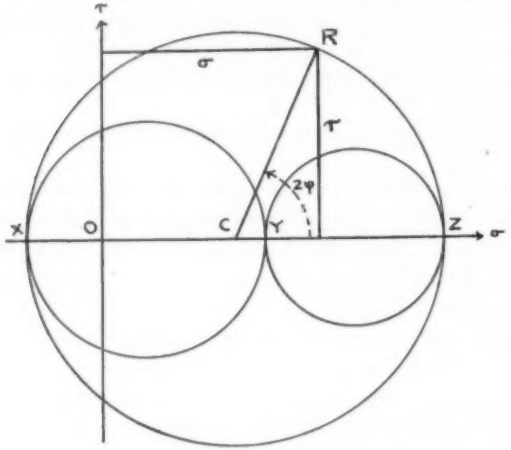

FIG. 11

diameters. It may also be shown that for any radius of the sphere not in the principal planes, the corresponding stresses σ, τ, are represented by the co-ordinates of points within the region bounded by all three of the circles XY, YZ, XZ. *The circle XZ therefore passes through all the points which have the greatest τ for any given σ occurring in the stress distribution.* This circle plays an important rôle in Mohr's theory of rupture, and is called by Mohr the *principal circle* in the graphic representation of the state of stress.

Mohr's theory of rupture deals with cases in which the failure of the material is assumed to be due to the sliding of one layer over another in certain planes called *shearing planes*. The fundamental

postulate of this theory may be stated as follows: *The ultimate strength of the material is determined by the greatest shearing stress in the shearing planes, this limiting shear itself depending upon the normal stress in the planes.* The limiting shear τ_m is thus assumed to be some function of the normal stress in the plane, $\tau_m = f(\sigma)$, but the nature of this dependence is not specified by the theory. The curve, however, which represents the relation $\tau_m = f(\sigma)$ has certain properties which may be inferred from Mohr's graphic representation of stress distributions. In this representation a point

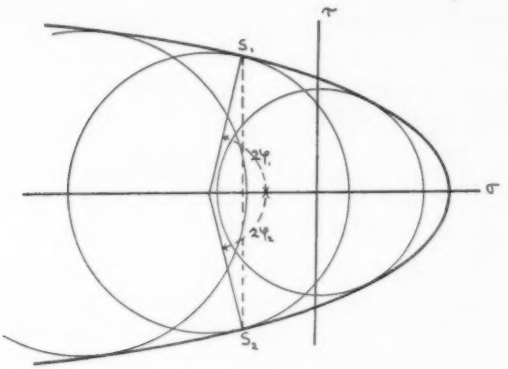

FIG. 12

S_1, corresponding to a shearing plane (Fig. 12), must lie on a principal circle, since the points of this circle have the greatest τ for a given value of σ. From this fact we may draw two important conclusions:

1. Since a principal circle is completely determined by the two extreme principal stresses, σ_x, σ_z, the ultimate strength of a material that fails by slippage must be entirely independent of the intermediate principal stress σ_y.

2. Since points on a principal circle correspond to planes normal to the xz plane, the shearing planes at any point must pass through the y-axis.

Furthermore, a point on a principal circle corresponding to a shearing plane must lie on the envelope of all the principal circles

representing ultimate states of stress. For this envelope is the locus of all points, which, for a given σ, have the greatest τ for the stress distributions in question. The envelope thus represents the relation $\tau_m = f(\sigma)$ between maximum shear and normal stress. As all principal circles have their centers on the σ-axis, their envelope is symmetric with respect to this axis, and touches each circle in two points, S_1, S_2, corresponding to the two shearing planes for the state of stress represented by the circle. Referring to Figure 12, we see that the shearing planes corresponding to S_1 and S_2 make equal angles with the zy plane: $\phi_1 = \phi_2$. The acute angle between the planes is therefore equal to $2\phi_1$, and is bisected by the principal plane zy.

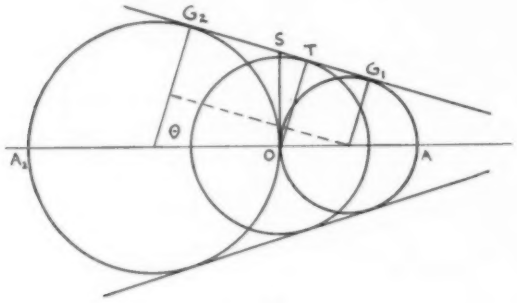

FIG. 13

Experiment has shown that the envelopes are roughly parabolic in shape. They presumably cut the $+\sigma$-axis at the point-circle representing rupture due to uniform all-sided tension ($\sigma_x = \sigma_y = \sigma_z$). Mohr also infers from the apparent impossibility of crushing a substance by applying uniform all-sided pressure, that if the envelope cuts the $-\sigma$-axis at all, it does so at an excessive distance from the origin.

If the ultimate tensile and compressive strength of a material are known, say σ_1 and σ_2, we may construct the principal circles corresponding to these limiting states, namely,

$$\sigma_x = \sigma_y = 0, \quad \sigma_z = \sigma_1; \qquad \sigma_x = -\sigma_2, \quad \sigma_y = \sigma_z = 0.$$

Thus in Fig. 13 we lay off $\overline{OA}_1=\sigma_1$, $\overline{OA}_2=-\sigma_2$, and draw the principal circles on $\overline{OA}_1$ and $\overline{OA}_2$. For states in which the principal stresses do not considerably exceed σ_1 and $-\sigma_2$, we may regard the common external tangents to these circles as representing approximately a portion of the envelope. For the region in which this approximation is allowable, the angle between the shearing planes is constant and given by

$$\cos\theta=\frac{\sigma_2-\sigma_1}{\sigma_2+\sigma_1}=\frac{\kappa-1}{\kappa+1},\quad \kappa=\frac{\sigma_2}{\sigma_1}. \tag{9}$$

The angle θ is thus independent of the particular state of stress and depends only upon the ratio of ultimate compressive to ultimate tensile stress. According as $\sigma_2 > = < \sigma_1$, θ will be an acute, right, or obtuse angle. For most materials $\sigma_2>\sigma_1$; values of θ corresponding to different values of κ in this case are given in the following table:

$\kappa=\frac{\sigma_2}{\sigma_1}$	1	1.5	2	3	4	5	10	20
θ	90°	78°	71°	60°	53°	49°	35°	25°

The principal circle for the state in which $\sigma_x=-\sigma_z$, that is, a circle about O as center and tangent to the envelope tangents, determines the ultimate torsional strength: $\rho_3=\overline{OT}$. The ultimate shearing strength is given by $\tau_4=\overline{OS}$; for this ordinate represents the maximum shear for zero normal stress. From the geometry of the figure,

$$\rho_3=\frac{\sigma_1\sigma_2}{\sigma_1+\sigma_2},\quad \tau_4=\tfrac{1}{2}\sqrt{\sigma_1\sigma_2}.$$

When σ_1 and σ_2 are nearly equal we have $\rho_3=\tau_4=\frac{1}{2}\sigma$, a result in concordance with many old and modern experiments and not satisfactorily explained by the earlier theories of rupture.

II. MOHR'S THEORY APPLIED TO EXPERIMENTAL DATA

Mohr's formula, $\cos\theta=\frac{\sigma_2-\sigma_1}{\sigma_2+\sigma_1}$, connects the angle of shearing with two important physical constants, the ultimate tensile strength and the crushing strength.

Within certain limits, that is to say, in so far as the curve $\tau_m=f(\sigma)$ between the points G_1 and G_2 approaches a straight line, it confirms

Hartmann's observation that the angle of shearing is independent of the nature and intensity of the stresses involved.

It also brings out clearly, in a qualitative way, the very different attitude of the planes of shearing in brittle and ductile substances. This becomes apparent when we introduce into it the average values of ultimate strengths contained in the following table:

TABLE I*

	k_2 Tons	k_1 Square Inches	k_2/k_1
Granite (av.)	7.5	0.3	25
Glass (various sorts)	4.3–8.7	2.5–6.0	15+
Marble (av.)	4.0	0.35	11
†Bluestone	6.8	0.7	9.7
Limestone (av.)	3.5	0.5	7
Glass (common green)	10	1.5	6.7
Iron, cast	40	7.5	5.3
Zinc, cast	(10)	2.5	(4+)
Georgia Yellow Pine (across grain)	0.7	0.3	2.3
Copper, cast	(20)	12	1.7
Steel, cast	35	35	1
Copper, bolts	15	15	1
Slate	5	5	1
White Oak (across grain)	1	1	1
White Oak (with grain)	3.5	5	0.7
Iron, wrought (av. good bars)	16–20	25	0.6–0.8
Georgia Yellow Pine (with grain)	2.5	6	0.4

*All figures in this table, excepting those in the third row, from H. H. Suplee, *The Mechanical Engineer's Reference Book* (4th ed., 1913).

They represent at best only average values and are used here only in a qualitative sense. Values of K_2 given in parenthesis indicate loads producing 10 per cent reduction in original lengths.

All figures are given in the original in lbs. per sq. in.

The values for various sorts of glass are taken from Winkelmann and Schott, quoted in O. D. Chwolson, *Lehrbuch der Physik*, Vol. I (Braunschweig, 1902), pp. 709 and 712.

†"Fine-grained, compact, very strong and durable" graywacke (of Hamilton age). G. P. Merrill, *Stones for Building and Decoration* (2d ed., 1897), p. 322.

According to the formula, the angle θ will differ the more from 90° the greater the ratio of the values of crushing and tensile strength.

Correspondingly, we find that substances like glass shear at very acute angles,[1] while for mild steel the angle varies between 80° and 100°.[2]

[1] 20°–30° in the case of glass of thick microscopic slides, according to tests made by the writer.

[2] See results of experiments by W. Mason and G. H. Gulliver, as given in W. Mason, "The Lüders' Lines on Mild Steel," *Proc. Phys. Soc. of London*, Vol. XXIII (1911), p. 306.

In the case of those substances in which the tensile strength is greater than the crushing strength, the formula would indicate that the shearing angle is obtuse. That this is indeed the case, for instance in the striking case of wood cut with the grain, may be seen from Figure 3, page 17, of Leith's *Structural Geology*.

This leads us to the important generalization that the angle of shearing of a material is the more acute the more brittle the substance is, and vice versa. In fact, it seems possible, if not probable, that in the hands of the physicist the angle of shearing will be made the chief criterion of brittleness.

The formula also brings out clearly the fact that the angle of shearing is independent of the hardness of the material. In the table given above wrought iron ranks with oak and pine wood. Small cubes of a "brittle" rubber, sold under the trade-name "soap rubber," produce shearing planes in the form of pyramids exactly like those seen in cubes of sandstone in ordinary crushing tests, with apical angles of 50° or even less. This shows that the shearing angle is also independent of the absolute amount of deformation of which the substance is capable below the elastic limit.

Strongly ductile[1] bodies, on the other hand, like soap, shear at very obtuse angles.

[1] The writer knows that in this paper he is using the word "ductile" in a sense which is sure to be severely criticized. He would be delighted to see such criticism lead to a fruitful open discussion of the fundamental conceptions involved in the deformation of solids. At this place the restricted sense in which the word "ductility" is used here may be defined best by giving it as one of several purely empirical characteristics of solids under deformation.

Substances differ in

1. The force required to produce the same absolute amount of deformation. (Small: rubber, wet clay; large: steel.)
2. The absolute amount of deformation required to reach the elastic limit. (Small: steel, wet clay; large: rubber.)
3. The percentage of any given deformation which remains permanent when the stress is removed. (0 per cent = perfect elasticity; 100 per cent = perfect plasticity.)
4. The additional force required to produce an additional amount of permanent deformation (negative, zero, positive).
5. The time required to produce the same absolute amount of permanent deformation without rupture.
6. The position of the point of rupture with reference to the yield point. (Point of rupture <or> yield point.)

In this paper a substance is called "brittle" when its point of rupture lies near its yield point. It is called "the more ductile" the farther beyond the yield point its point of rupture lies. In a "perfectly ductile" substance it lies an infinite distance beyond. In a "perfectly brittle" substance it is reached before the yield point.

When rocks are subjected to deformation in nature, the question whether they will break or bend depends largely on the degree of brittleness they possess under the given conditions and not on their hardness. This explains why geologists have been justified in the attempt to reproduce in the laboratory the various structures exhibited by the hard materials of the earth's crust by the use of soft clay, mixtures of clay and plaster of paris, and even wet sand. The use of the angle of shearing as an index of brittleness opens up new possibilities for standardizing the materials used in such experiments to accurately reproduce definite actual conditions.[1]

Mohr's formula could be quantitatively correct only, if the curve $\tau_m = f(\sigma)$ were practically a straight line between the circles of ultimate tensile and compressive stress. This, however, is not true. The form of the curve, therefore, must first be determined experimentally for each substance. From it the variable θ can be computed, from point to point by analogous formulas.

This was carried out for the first time, as far as the writer knows, in a series of excellent experiments by Kármán.[2]

He used an apparatus in which small cylinders of rock could be subjected simultaneously to hoop and longitudinal pressures in such a way that either pressure could be controlled without changing the other. The results of his experiments are embodied in stress-strain diagrams which in the most striking way show the fact that the materials used—marble and sandstone—change step by step with increasing hoop pressure from a state of perfect brittleness to one of perfect ductility. In this respect Kármán's experiments supplement beautifully the brilliant investigations of Adams.

With low hoop pressures shearing occurred in the rock cylinders resulting in the formation of Lüders' lines on the polished surfaces and, with lowest hoop pressures, leading to rupture.

In the following table[3] the observed values of the angles of shearing at various hoop pressures are placed side by side with the values computed according to Mohr's graphic construction.

[1] The angle of shearing can readily be determined for many substances by means of an ordinary vise, if small cubes (1 cm³) are used.

[2] Th. von Kármán, "Festigkeitsversuche unter allseitigem Druck," *Zeitschr. des Vereins deutscher Ingenieure*, Vol. LV (1911), pp. 1749–57.

[3] Tables 1 to 4 of Kármán's paper.

The agreement is sufficiently close to strongly support Mohr's theory. In addition, however, the figures reveal the striking fact that as the material changes, under the action of all-sided pressure, from a brittle to a ductile substance, the angle of shearing grows progressively less and less acute. Kármán's experiments have, therefore, completely verified in the case of one and the same substance the inference that the less brittle a substance is the larger is its angle of shearing.

TABLE II

	Hoop Pressure $\sigma_3 = \sigma_2$ in Atmospheres	Effective Longitudinal Pressure $\sigma_1 - \sigma_3$ in Atmospheres	θ Observed without Reduction*	θ Observed with Reduction	θ Computed
Marble	0	1360	54°	54°	53°
	235	2100	59°	58°	58°
	500	2650	72°	65°	63°
	685	2880	83°	70°	73°
Sandstone	0	690	38°	38°	40°
	280	2040	70°	69°	63°
	555	2580	82°	73°	70°

* To find the true angle at which rupture actually took place, it is necessary to reduce the observed angle to the value it had when the rock cylinder was deformed under its load.

We can, however, go even one step farther. If growing circumferential pressure at right angles to the direction of maximum (compressive) stress increases the ductility of a substance, and with it the angle of shearing, circumferential tension must decrease it, that is, render the substance more brittle. This is completely born out by the experiments published in 1911 by W. Mason.[1] He subjected tubes of mild steel to longitudinal compressive stress simultaneously with the application of interior hydrostatic pressure, and in one series of experiments, made the tubes undergo longitudinal tension while applying water pressure externally. The angle facing the direction of maximum compressive stress, in the absence of circumferential pressure, measured[2] approximately 100°. With growing tension normal to the direction of compression,

[1] W. Mason, "The Lüders' Lines on Mild Steel," *Proc. Phys. Soc. of London*, Vol. XXIII (1911), pp. 305–33.

[2] *Ibid.*, Table B, values at bottom of column.

the angle changed from 100° to values as low as 84° and even[1] 79°. These values remained the same, whether the compressive stress acted longitudinally or as hoop stress.

Here, then, we have a substance which normally shears under compression at an angle of 100° changed to one shearing at 80° through the action of tension in all directions normal to that of the axial compression, or, using the word in the sense defined above, we may say, the substance has been made more brittle.

III. THE ELLIPSOID OF STRAIN

The attempt to correlate joint planes with stress-strain relations, to which the first part of this paper was devoted exclusively, is by no means new. Steidtman's splendid paper on "The Secondary Structures of the Eastern Part of the Baraboo Quartzite Range, Wisconsin"[2] is well known, and Leith, in his lectures and in his *Structural Geology*[3] has impressed on the younger generation of geologists the importance of shearing planes in the mechanics of rock fractures by the use of a wire-netting model.

Unfortunately, however, the model as well as the earlier discussions by other writers, give expression only to that case in which the planes of shearing form an obtuse angle in the direction of compressive stress.

The outstanding characteristic of the strain ellipsoid illustrated by Leith's wire-netting model, is the fact that the elongation in the direction of one principal stress equals the shortening in the direction of the other principal stress, or, that the area of the strained surface remains unchanged. A simple mathematical consideration shows that when a circle is changed into an ellipse of equal area, the angle of the lines of no distortion facing the direction of shortening, must always exceed 90°[3] (Fig. 14). To reduce this angle to the smaller value characteristic of all brittle materials, we must assume the longitudinal shortening to be smaller than

[1] W. Mason, "The Lüders' Lines on Mild Steel," *Proc. Phys. Soc. of London*, Vol. XXIII (1911), Table D, bottom of column (complementary angle).

[2] *Jour. Geol.*, Vol. XVIII (1910), pp. 259–70.

[3] New York: Henry Holt & Co., 1913, pp. 18–20.

the transverse elongation (Fig. 15), that is, increase the area of the Figure under deformation.[1]

This, however, leads to the conclusion that under simple non-rotational stress a brittle body suffers an increase of volume. Since the angle of shearing is the more acute the more brittle a substance is, we must expect the increase of volume under stress to be the greater the more brittle a material is.

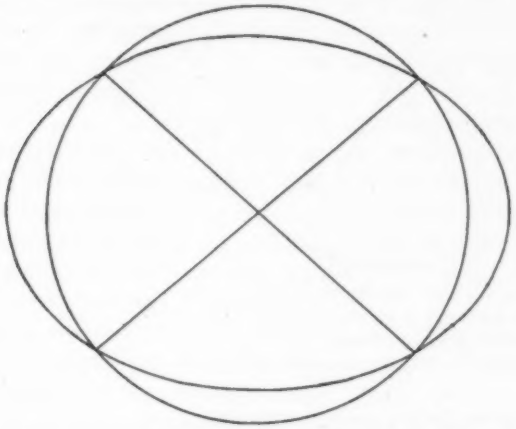

FIG. 14.—Diagram showing the position of the lines of no distortion in an ellipse of strain derived from a circle of equal volume. The angle of shearing is obtuse.

This seems indeed to be the case. Chwolson[2] gives the following formula connecting the modulus of volume increase (under tension), η, with the modulus of longitudinal strain (Young's modulus), a, and Poisson's ratio $\left(\frac{\text{lateral strain}}{\text{longitudinal strain}}\right)$, σ:

$$\eta = a(1 - 2\sigma).$$

According to this formula, $\sigma = 0.5$, when $\eta = 0$, that is, when the volume remains unchanged during deformation. The change of

[1] For the mathematical proof of this statement the writer is again under obligation to Dr. Brand.

[2] O. D. Chwolson, *Lehrbuch der Physik*, Vol. I, p. 713.

volume, therefore, must be the greater the more σ differs from 0.5, that is, the smaller it is. The following values[1] of σ for different substances completely confirm the inference drawn from the graphic representation of the strain ellipsoid.

FIG. 15.—Diagram showing the position of the lines of no distortion in an ellipse derived from a circle of smaller volume (increase of volume accompanies deformation). The angle of shearing is acute.

Paraffin	0.50
Caoutchouc	0.50
Copper	0.348
Mild Steel	0.304
Iron	0.243 to 0.310
Zinc	0.205
Glass	0.197 to 0.319

That brittle bodies suffer an increase of volume when deformed under tension, is well known. That such an increase of volume also actually accompanies deformation under one-sided compression, as demanded by the graphic construction of the strain ellipsoid, seems to be proved by the experiments made by Kahlbaum and Seidler[2] and more recently by Lea and Thomas.[3]

It is essential, therefore, before we use the strain ellipsoid for the interpretation of shearing planes in nature, that we decide which form of the ellipsoid corresponds to the conditions of the specific case.

IV. PLANES OF SHEARING PRODUCED BY IRROTATIONAL AND ROTATIONAL STRAINS

We may now return to the interpretation of planes of shearing observed in nature. We have learned that Hartmann's law applies to brittle substances only, that is, that only in brittle materials the

[1] O. D. Chwolson, *Lehrbuch der Physik*, Vol. I, p. 714.

[2] R. Kahlbaum and Seidler, *Zeitschr. Anorg. Chem.* (1902), pp. 29–30, 254–94.

[3] F. C. Lea and W. N. Thomas, "Change in Density of Mild Steel Strained by Compression beyond the Yield-Point," *Engineering*, Vol. C (1915), pp. 1–3.

Department

acute angle of shearing planes faces the direction of the compressive stress. We may now extend the law by adding, that in ductile substances it is the obtuse angle that faces the direction of the compressive stress.

Before attempting to apply the law to any specific case, therefore, we must decide whether the material under the given conditions had the properties of a brittle or those of a ductile substance. On the other hand, when the direction of the greatest principal stress is known, the position of the joint planes produced by it may be used to determine the degree of ductility which the material possessed at the time of shearing.

All the cases so far discussed involve irrotational strains only. The arrangement of shearing planes due to rotational strains, as illustrated by Leith's wire-netting model and discussed in his book on *Structural Geology*, is, of course, only possible in ductile substances, as a glance at the angle of the shearing planes will show. This model has, however, been applied successfully to some striking cases of jointing in quartzites.

We may approach the problem involved in these interesting cases by turning to an illustration in Van Hise's "Principles of North American Pre-Cambrian Geology," page 652.[1] Figure 131 shows layers of quartzite alternating with thin beds of more slaty character. The harder beds are traversed by two systems of intersecting joints, both forming angles of 50°–70° with the bedding planes, that is, forming acute angles of approximately 60° facing the bedding planes.

In the intercalated slaty beds, however, only one of these two joint systems is developed. It consists of more numerous joints inclined but 20° or less to the bedding planes. If the complementary symmetrical set were developed, the angle formed by the two systems facing the bedding planes would be 130° in these less brittle slaty beds, instead of 60° as in the brittle purer beds.

From this relation of the shearing angles in the two types of rock it is evident that the joints in the more brittle beds are due to the normal component of the stress acting on the beds. They

[1] *Sixteenth Ann. Rept. U.S. Geol. Survey*, Part I (1896), p. 652. See also C. K. Leith, "Rock Cleavage," *U.S. Geol. Survey, Bull. 239* (1905), p. 123, Fig. 37.

must, therefore, have been developed essentially through irrotational strain.

The differential movement between adjoining beds required by the structural relations indicated in the text, was obviously largely limited to slippage parallel to the bedding within the thin slaty layers. It is important to note, however, that the direction of movement here, as in several cases referred to in the first part of this paper, has influenced the number and nature of the two opposed diagonal joint systems in the brittle beds. Those inclined in the direction of drag produced by the differential movement are more numerous, closed, and slickensided, while the opposite set is represented by few and gaping joints.

The closely spaced joints in the slaty beds, on the other hand, may partly be due to true rotational strain.

Essentially the same considerations apply to the case discussed in detail by Steidtmann[1] and by Leith in his *Structural Geology*. Here the joint system opposed to the "drag" action of the differential movement between the beds is represented by but a few "open gashes or tension joints." But their presence is sufficient to indicate that in the center of the quartzite beds the effect of rotational strain has been entirely subordinate to that of the irrotational strain produced by the component normal to the bedding planes.

The writer has the suspicion that this will be found to be true most generally in bedded rocks, in which differential movement between the beds is largely accomplished by slippage along bedding planes chiefly within layers of soft rock acting as lubricants.

V. PLANES OF SHEARING IN SHALES

The absolute and relative values of the crushing and tensile strengths of a rock play a fundamental roll in the deformation of rocks along the face of natural and artificial excavations.[2]

When the depth of an excavation has reached the point at which the vertical component of the stress set up by the removal of

[1] *Jour. Geol.*, Vol. XVIII (1910), p. 261, Fig. 1.

[2] See the excellent analysis of the factors involved in D. F. MacDonald, "Excavation Deformations," *Congrès géologique international, Compte rendu de la XII^e session* (Canada, 1913), pp. 779–92.

FIG. 16.—Fold and thrust fault in Eden shales, West Fork Creek, Cincinnati, Ohio

FIG. 17.—Fold and thrust fault in Eden shales, West Fork Creek, Cincinnati, Ohio

material at the toe of the new steep slope exceeds the elastic limit, rupture along planes of shearing will take place sooner or later in brittle materials. Ductile substances, on the other hand, such as

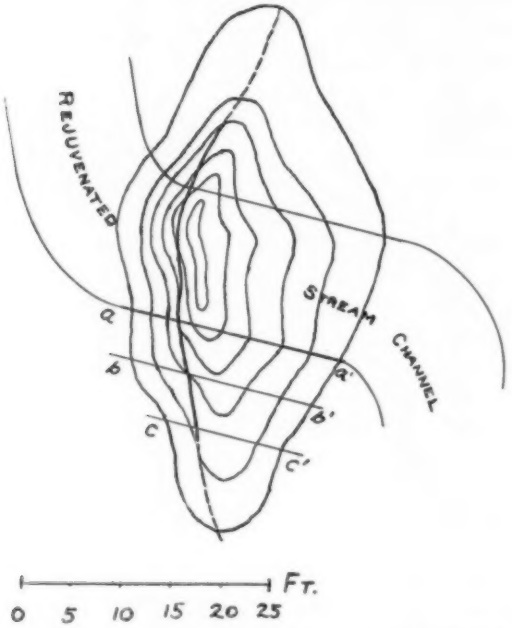

FIG. 18.—Diagrammatic contour map of the surface of a bed of shale buckled and cut by an inclined joint plane. Superimposed on it is the outline of a new stream bed cut into this structure after rejuvenation.

clays, will flow, causing the lower part of the steep slope to bulge out and the bottom of the excavation to buckle up.[1]

Van Horn has given a detailed description of this buckling at the base of a rock slide.[2] Small and entirely local anticlines which

[1] D. F. MacDonald, "Excavation Deformations," *Congrès géologique international, Compte rendu de la XII^e session* (Canada, 1913) p. 791, Fig. 3.

[2] Frank R. Van Horn, "Landslide Accompanied by Buckling, and Its Relation to Local Anticlinal Folds," *Bull. Geol. Soc. Amer.*, Vol. XX (1910), pp. 625–32.

quite obviously owe their origin to this process, are of common occurrence in the bottoms of ravines cut into clays or shales, and are often directly associated with landslip terraces.[1] Identical surficial anticlinal buckles[2] which have been observed under a cover of glacial drift without any connection with steep slopes or landslides, probably owe their origin to similar stress relations resulting from the cracking or other deformation of the Pleistocene ice cover.

In the vicinity of Cincinnati, wherever the most recent rejuvenation has cut into the bottom of ravines within the Eden shales, similar bucklings are quite common.[3] Frequently, however, these anticlines are not only overturned, but faulted, generally in the form of a miniature overthrust, such as shown in the Figures 16 and 17.

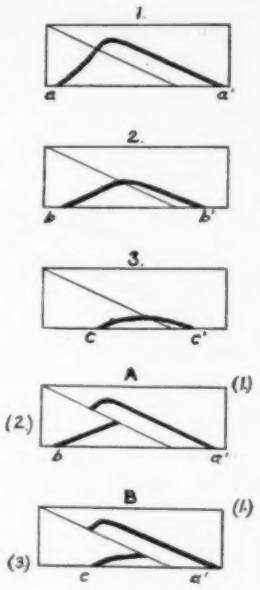

FIG. 19.—Sec. 1 shows the structure exposed on the south side of the stream channel shown in Fig. 18. Secs. 2 and 3 are drawn parallel to and 5 and 10 feet, respectively, south of, sec. 1. Sec. A shows the result of squeezing out the shale layers from underneath the joint plane in such a way that the lower portion of sec. 2 is pushed out so as to rest under the upper portion of sec. 1. In sec. B this process is carried farther, the lower portion of 3 pushed out so as to rest underneath the upper portion of 1.

In the light of the preceding discussion, it appears highly probable that these miniature "reversed faults" have nothing to do with horizontal compressive stresses. The shales are distinctly ductile, as is implied by the very existence of the anticlines due to flowage. They are, however, ductile only to a limited degree. After the strain has reached a certain limit, they rupture along planes of shearing. Here the obtuse angle formed by two

[1] E.g., T. C. Hopkins and W. M. Smallwood, "Discussion of the Origin of Some Anticlinal Folds near Meadville, Pennsylvania," *Bull. Syracuse University*, Ser. IV, No. 1, 18 (quoted from Van Horn, *loc. cit.*).

[2] For instance, G. K. Gilbert, "Dislocation at Thirtymile Point, New York," *Bull. Geol. Soc. Amer.*, Vol. X (1899), pp. 131–34; F. R. Van Horn, "Local Anticlines in the Chagrin Shales at Cleveland, Ohio," *ibid.*, Vol. XXI (1910), pp. 771–73.

[3] E. L. Braun, "The Cincinnatian Series and Its Brachiopods in the Vicinity of Cincinnati," *Jour. Cinc. Soc. Nat. Hist.*, Vol. XXII (1916), No. 1.

symmetrical joint planes points to the action of compressive stress in a perpendicular direction, or especially to the horizontal tensile

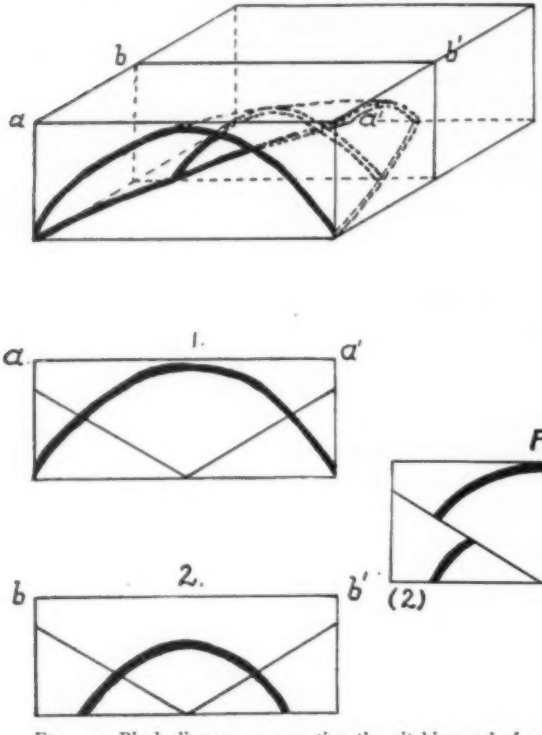

FIG. 20.—Block diagram representing the pitching end of an anticline.

Sec. a–a′=sec. 1 below.
Sec. b–b′=sec. 2 below.

These sections show, in addition, the position of two inclined joint planes striking parallel to the axis of the fold. Sec. A shows the result of squeezing out the shale layers from underneath the joint plane in such a way that the lower portion of sec. 2 is pushed out so as to rest under the upper portion of sec. 1.

stress which results when the upper layers are forced up by the pressure of the flowing layers of shale underneath.

Whenever a stream removes a portion of such an anticline, as indicated on the map sketch in Figure 18, the tendency exists to

squeeze the dipping beds up from underneath the joint plane, out into the channel.

Sections A and B (Fig. 19) show the result which is brought about entirely by a horizontal flowage of the beds beneath the joint plane in a direction perpendicular to the plane of the paper, and not to any horizontal compressive stresses acting within the plane of the paper.

The joint nature of these "fault" planes is brought out beautifully by the exposure shown in Figure 17, which for years has been well exposed in Westfork Creek at Cincinnati, just above the schoolhouse.

There can be little doubt that essentially the same interpretation applies to other similar occurrences.[1]

VI. HORIZONTAL COMPRESSIVE STRAINS IN GRANITE

Compressive strains of considerable magnitude, essentially in a horizontal direction, exist at widely separated localities in all states of New England, if not throughout the whole region. In the quarries, the strains find expression in various ways. Vertical drill holes are flattened to an elliptical cross-section,[2] the cores between contiguous borings are crushed, and cracks open up diagonally from the channels.[3] In the process of quarrying new fissures open up with a dull explosive noise,[4] or new sheetlike partings form[5] or old sheets buckle up.[6]

With a detailed knowledge of most of the excellent exposures of sheeted granite in New England at his command, Dale has come to the conclusion that shrinkage in cooling, or changes of temperature, or other forms of weathering have played, at best, only a secondary rôle in the production of the sheet structure; that the

[1] A. H. Purdue, "Illustrated Note on a Miniature Overthrust Fault and Anticline," *Jour. Geol.*, Vol. IX (1901), pp. 341–42; C. E. Decker, unpublished manuscript, see Fig. 17, p. 39, *Jour. Geol.*, Vol. XXVI (1918).

[2] T. N. Dale, "The Granites of Vermont," *U.S. Geol. Survey, Bull. 404*, p. 18, Fig. 2; *Bull. 354*, p. 34.

[3] *Ibid.*, *Bull. 354*, pp. 96 and 126; *Bull. 313*, pp. 12 and 142.

[4] *Ibid.*, *Bull. 313*, pp. 34 and 142.

[5] *Ibid.*, *Bull. 404*, pp. 97 and 107.

[6] *Ibid.*, *Bull. 313*, Pl. VII, A.

main factor has been horizontal compressive stress such as now finds expression in the region.[1]

This is not the place nor the time to enter into a discussion of this complex problem. The final word has not yet been spoken.

If we assume, for the time being, a diastrophic origin of the observed strains, we can point to three observations favoring such a view.

1. For at least one locality, the famous Quincy quarries south of Boston, Dale records the observation that "this strain in some quarries appears to increase with their depth."[2]

2. At Fletcher Quarry, on Robeson Mountain, in Washington County, Vermont, Dale observed what he called "double-sheet" structure. Here, instead of the usual single set of sheets, two such sets, intersecting at an angle of about 42° are exposed. If we analyze their position according to the method described in the first part of this paper we find that the bisectrix of the acute angle, that is, the direction of the greatest principal (compressive) stress, trends N. 60 W.–S. 60 E. and that it differs but slightly from the horizontal, being slightly directed downward toward the southeast. The least (tensile) principal stress, on the other hand, is practically directed upward, in the direction of easiest relief from the horizontal pressure.[3]

Fortunately, there is, at the same locality, "a marked northeast-southwest compressive strain in the upper part of the quarry, raising the sheets and even forming new sheet partings." The direction of this strain is essentially that which would result from the compressive stress, acting from the northwest, inferred from the "double-sheets." While this may, of course, be a mere coincidence, it certainly is suggestive of a causal connection.

None of the other quite numerous cases in which Dale records the direction of compressive strain, together with data concerning the position of the sheet structure, can be used to test this matter

[1] T. N. Dale, "The Granites of Connecticut," *U.S. Geol. Survey, Bull. 484* (1911), pp. 29–36.

[2] *U.S. Geol. Survey, Bull. 354*, p. 96.

[3] If we had reason to believe that the granite had been in a ductile state when these planes of parting were formed, the stresses would have to be reversed. But all observations seem to speak against this possibility.

further. For with only one of the two intersecting planes of shearing given, we cannot even guess at the position of the principal stresses.[1]

3. The New England region is that part of the United States of which we know most definitely and quantitatively that it has undergone considerable deformation in post-glacial time. A glance at Fairchild's map of "Isobases of Post-glacial Uplift"[2] shows that if we can assume the earth's surface to the south and southeast to be relatively at rest and the domelike upheaval with its center halfway between Quebec and James Bay to be rising independently, there should exist a compressive stress in the general direction northwest–southeast throughout the surface of New England. It may, of course, be mere coincidence that this is the same direction which we found required to produce the "double-sheet" structure on Robeson Mountain. But, combined, these three observations are distinctly favorable to the view that the larger part of the remarkable sheet structure of the granites of New England is due to compressive stresses arising from the larger earth movements indicated by Fairchild's isobasic maps.

The objection may be raised that in quarries in other parts of New England strains in different directions have been observed.

Great variations in local conditions of stress are not surprising in view of two important facts. The direction of relief in these cases is normal to the surface. Where the surface is far from horizontal the position of one of the two principal stresses must vary from place to place, and with it, the position of the resulting plains of shearing.

Furthermore, observation shows that the granites, which exhibit the sheet structure, are divided by various joint systems, some unquestionably of earlier origin. It is, therefore, not an unbroken sheet of granite that is being deformed in this region, but a mosaic of large and small blocks. The stress conditions, resulting

[1] If, for instance, in the case illustrated in Fletcher Quarry only the planes striking N. 20 W. had been given, we would probably not have considered them to be in harmony with a compressive stress acting from the northwest.

[2] H. L. Fairchild, "Post-glacial Uplift of Northeastern America," *Bull. Geol. Soc. Amer.*, Vol. XXIX (1918), p. 202.

from such a complex arrangement, must be expected to vary considerably from place to place, while corresponding only in the aggregate to the simple fundamental stress relation.[1]

Whatever may be the true merits of this interpretation of the "double-sheet" structure, it serves well to bring out the fact that horizontal compressive stresses will produce planes of shearing at low angles only in highly brittle substances close to the surface, where the least principal stress is directed upward, in the direction of easiest relief.

VII. LOW-ANGLE FAULTING

This leads us finally to the important question of low-angle faulting which has recently been given a most valuable discussion by R. T. Chamberlin and W. Z. Miller.[2]

The heart of the problem is nowhere clearer exposed than in the northwest Highlands of Scotland.[3] A series of sediments of diverse nature, piled up, shingle-like, by thrust faults inclined on the average about 45°, has been cut across by several practically horizontal planes of fracture, along which the individual slices have been moved in the general direction of thrust for many miles.

The strongly inclined faults clearly are planes of pure (irrotational) shear produced by the horizontal compressive stress. The

[1] For a similar reason, the movement on individual shearing planes, into which a block has been broken under one-sided pressure, may be most diverse, one block being pushed out in one direction, the other in another. This explains the small success that has attended the attempts made by Dr. Salomon (1911) and some of his students (Lind, 1910, Dinu, 1912, Spitz, 1913, Engstler, 1913, Seitz, 1917) to determine the nature of the stress involved in the formation of joint systems from the direction of movement recorded on the slickensides. (For complete references to these most careful studies, see O. Seitz., *Über die Tectonik der Luganer Alpen*, Inaug. Diss., Heidelberg, 1917).

The same criticism applies equally to the attempts made to infer from local observations of movements during an earthquake the nature of the major stresses which have resulted in the formation of great fault lines. The cause of such movements along existing fault lines may be fundamentally different from that which caused the fracture itself.

[2] R. T. Chamberlin and W. Z. Miller, "Low-Angle Faulting," *Jour. Geol.*, Vol. XXVI (1918), pp. 1–44.

[3] B. N. Peach, John Horne, W. Gunn, C. T. Clough, and L. W. Hinxman, "The Geological Structure of the North-West Highlands of Scotland," *Mem. Geol. Survey of Great Britain*, 1907.

question is, Can the essentially horizontal planes of fracture have been produced under similar conditions of strain or do they represent the result of rotational strain?

To prove the first assumption, we must find a cause for the great change in inclination of the shearing planes from rather high angles to a horizontal position. Cadell's experiments and their own researches led Chamberlin and Miller to the suggestion that the additional vertical pressure resulting from the piling up of numerous thrust-blocks may tend to reduce the angle of shearing.

In the light of the preceding discussion it appears that an additional load would rather have the opposite effect. It would be equivalent to increasing the hoop pressure in Kármán's experiments. It would render the rock less brittle and therewith the angle of shearing larger. Since the compressive stress, in this case, acts in a horizontal direction this would mean planes of shearing inclined at a steeper angle than before.

Any given rock shows the smallest angle of shearing at the surface. To reduce this angle still more, an active tensile stress would have to be applied in a vertical direction, which is, of course, out of question.

In a general way, then, we must picture to ourselves the planes of pure shear produced in the earth's crust by a horizontal compressive stress as being least inclined near the surface and becoming progressively steeper at lower levels so as to approach finally the more or less vertical position of the planes of flowage existing at considerable depths. Conceptions such as are expressed, for instance, in Ulrich's diagrams to illustrate the "inland migration of belts of folding in Southeastern North America" in his "Revision of the Paleozoic Systems"[1] require corresponding modification.

For an understanding of the mechanics of the large horizontal overthrusts, however, we can but turn to the only alternative, which was clearly brought out by Chamberlin and Miller, that, in contrast to the other type, they are essentially the result of rotational strains of the kind which Becker has termed "scission," which occur "when a bar or plate is shorn by a pair of shears, or

[1] *Bull. Geol. Soc. Amer.*, Vol. XXII (1911), p. 441.

when a rivet yields perpendicularly to its axis, say, in a bursting boiler."[1]

A clear and simple illustration of the form in which this method of fracturing finds its most important expression in the earth's structure, is offered by Figure 21, which represents the section of one of the folds of the Jura Mountains at the boundary of France and Switzerland, as brought out by Buxtorf's detailed investigations.[2] The brittle layer of the Rauracien, which stood up vertically in the process of folding, comparable to the rivet on a boiler plate mentioned above, gave way to the pressure of the swelling plastic Oxford clays, counteracted below by the level part of the north limb of the anticline.

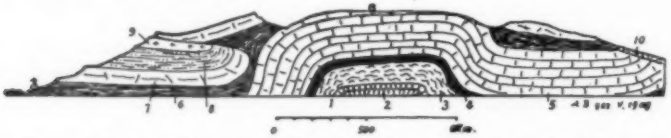

FIG. 21—Cross-section of a fold of the Jura Mountains at the border of France and Switzerland (at the "Clos du Doubs"). 1-3, Triassic, 4. Liassic, 5. Dogger, 6. Oxford clays, 7. Rauracian, Sequanian, 9. Kimmeridgian, 10. Landslide. (A. Buxtorf, 1909.)

The writer is inclined to believe, following the lead of Dr. Buxtorf,[3] that in the case of most, if not all "low-angle faults," or as Suess[4] called them, "listric planes," *the rotational stress resulted from the flowage of materials inside the fold*, whether it be, on a smaller scale, confined to individual normally plastic layers, or, on the largest scale, to the forced flowage of the rocks forming the cores of rising mountains.

This, however, leads us beyond the scope of this paper. The necessary setting for a broader discussion of this important problem will be given in a paper now in preparation.[5]

[1] G. F. Becker, "Finite Homogeneous Strain, Flow and Rupture of Rocks," *Bull. Geol. Soc.*, Vol. IV (1893), p. 24.

[2] A. Buxtorf, "Über den Gebirgsbau des Clos du Doubs und der Vellerat-Kette im Berner Jura," *Ber. Vers. Oberrhein. Geol. Ver.* (1909), p. 76, Fig. 1.

[3] *Ibid.*, p. 86.

[4] E. Suess, *The Face of the Earth* (transl. by Sollas, H. B.), Vol. IV (1909), p. 536.

[5] Parts of which were presented before the Geological Society of America at the Chicago meeting 1920 under the title "The Probable Cause of the Localization of the Major Geosynclines."

FEATURES OF A BODY OF ANORTHOSITE-GABBRO IN NORTHERN NEW YORK[1]

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GENERAL RELATIONS OF THE ANORTHOSITE-GABBRO

The body of rock considered in this paper varies from true anorthosite, through anorthosite-gabbro, to true gabbro. It is four and one-third miles long, with a maximum width of one mile. It lies a little west of the central part of the Russell quadrangle in St. Lawrence County, New York (Fig. 1).

As far as could be determined, the rock immediately surrounding the gabbro is granite which is generally pink in color and carries only moderate amounts of dark minerals. The granite varies from medium grained to coarse grained, and from scarcely foliated to highly foliated. That the granite is younger than the anorthosite-gabbro is proved by the presence of both granite and granite-pegmatite dikes in the gabbro, and by the more or less intimate injection of portions of the borders of the gabbro by the granite. The best and most instructive exposures occur within the northern one-third of the area.

About twenty-five years ago Professor C. H. Smyth published a short paper[2] which is largely a microscopical petrographic description of a ledge of gabbro probably lying within the area of anorthosite-gabbro. It is the present purpose to rather fully discuss the megascopic and microscopic features, field relations, and origin of the remarkable lot of rocks which constitute facies of the body of anorthosite-gabbro and directly associated rocks covering several square miles.

VARIATIONS IN COMPOSITION

The whole mass of the rock of the area is called anorthosite-gabbro because it shows every possible gradation from true gabbro

[1] Published by permission of the state geologist of New York.

[2] C. H. Smyth, *Amer. Jour. Sci.*, 4th series, Vol. I (1896), pp. 273–81.

(light gray to dark gray) to almost pure plagioclase anorthosite (light gray to nearly white). In the northern portion of the area the light-gray anorthositic facies are most conspicuously developed, but they occur locally in all parts of the area.

In thin section under the microscope the feldspars of the gray to nearly black facies contain myriads of dustlike inclusions,

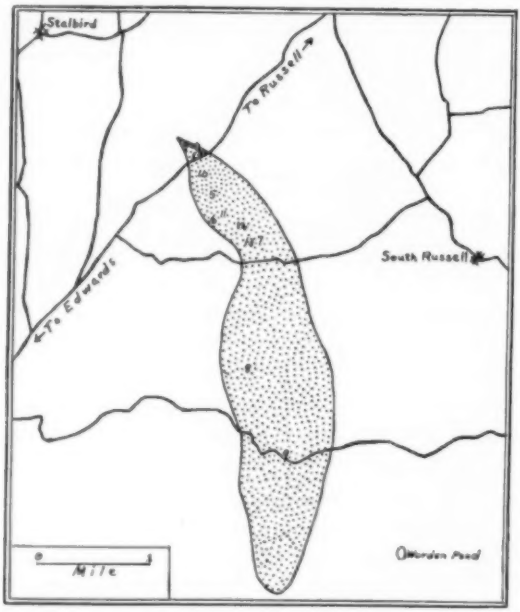

FIG. 1.—Sketch map of part of central St. Lawrence County, New York, showing the location of the body of anorthosite-gabbro. Numbers indicate localities referred to in the text.

probably ilmenite. No. 42 of Table I (see below) represents a thin section of a specimen of the typical very common dark-gray, medium-grained to moderately coarse-grained, non-foliated gabbro with ophitic texture from locality 9 (see Fig. 1). The labradorites, which range in length up to one-half an inch, are generally euhedral. All the pyroxenes (probably diallage) have narrow rims of hornblende around them, but some hornblende occurs either in small

clusters or as scattering grains. There is some very local granulation, especially of the feldspars.

No. 39 of the table represents a thin section of a light greenish-gray, medium-grained, moderately ophitic gabbro from locality 8. The andesine is much altered, mostly to scapolite. The pyroxene (probably diallage) is pale green to colorless. Tiny black inclusions in it are common. Most of the hornblende forms distinct granular rims around the pyroxenes, but a good deal of it is elsewhere interlocked with the pyroxenes. There is some granulation of the feldspars in local zones only.

No. 51 of the table is from a specimen of the very common dark-gray, non-foliated, medium-grained to fine-grained gabbro with ophitic texture from locality 7.

At locality 6 the main body of the rock is a medium-grained to moderately coarse-grained gabbro with a crude ophitic texture. The feldspar laths range up to three-fourths of an inch in length. No. 47 of the table shows the minerals contained in a thin section. Common green hornblende occurs mostly as narrow rims around both pyroxene and magnetite. Small inclusions of hornblende occur in the plagioclase. Granulation is lacking. Lying within the rock just described there is a zone of distinctly porphyritic, non-foliated gabbro about a rod wide, without sharp contacts. A hand specimen shows scattering, irregularly arranged, broad, dark laths of plagioclase up to one-half of an inch in length imbedded in a fine-grained dark-gray groundmass. No. 46 of the table shows the minerals observed in a thin section. Much of the feldspar has been altered, chiefly to scapolite. There is apparently no granulation, but considerable masses of fine granular hornblende, pyroxene, biotite, and plagioclase fill large spaces between, and cracks in, the feldspar phenocrysts. A good many grains of biotite, hornblende, and pyroxene are also irregularly scattered through the feldspars.

In a ledge at locality 1 most of the rock is a coarse-grained hornblende-rich facies of the gabbro. This rock is light gray, due to whiteness of the feldspars, which range in length from the merest fraction of an inch to several inches. Most of the feldspars are distinctly euhedral. A coarse ophitic texture is usually well

exhibited over the weathered surface. No. 57 of the table represents a thin section. The large euhedral crystals of plagioclase (chiefly labradorite) are generally fringed with rather clear granular scapolite, while their interiors are considerably decomposed. On one side this rock is moderately foliated, the feldspars being drawn out into crude parallelism. This foliated portion is not sharply separated from the rest of the rock. Within the foliated portion, and not sharply separated from it, there is a tongue or dikelike mass of gabbro very rich in dark minerals, chiefly hornblende.

TABLE I

MINERALS BY VOLUME PERCENTAGES IN THIN SECTIONS OF THE ANORTHOSITE-GABBRO AND CLOSELY ASSOCIATED ROCKS

Slide Number	Localities Shown on Sketch Map	Labradorite	Andesine	Oligoclase to Labradorite	Andesine to Labradorite	Scapolite	Augite or Diallage	Hornblende	Biotite	Quartz	Chlorite	Magnetite	Pyrite	Hematite	Zircon	Apatite	Titanite	Epidote
30	8	....	66	....	....	....	23	6	½	....	Little	2	....	....	Little	.....	....	½
43	9	74	....	....	....	....	16	5	2	½	.....	2	½	....	.....	.....	....	....
46	6	....	....	....	82	....	7	7	4	....	.....	.....	....	....	.....	.....	....	....
47	6	....	....	....	76	....	15	3	1½	....	.....	4	....	....	.....	½	....	....
51	7	....	....	50	....	....	24	10	6	....	.....	8	½	1½	.....	.....	....	....
57	1	....	....	64	....	10	....	25	....	....	.....	1	....	....	.....	.....	....	....
56	1	....	....	76	....	....	10	12½	....	....	.....	½	....	....	1	.....	....	....
58	1	....	....	....	59	....	14	23	....	....	.....	Little	....	....	4	.....	....	....
59	1	46	....	....	....	....	26	26	....	....	.....	1	....	....	1	.....	....	....
52	7	....	....	....	....	39	.....	43	....	13	.....	4½	½	....	.....	.....	....	....
49	5	....	....	64	....	35	.....	½	....	....	.....	....	....	....	Little	Little	½	....

In the coarse-grained gabbro at locality 1, less than a rod from the rocks above described, there is a highly foliated zone or belt of very variable rocks about a yard wide. Much of this rock is fine grained, dark gray, highly foliated, and uniform in appearance, a thin section being represented by No. 51 of the table. There appears to be no true granulation. Another facies of this zone is a highly foliated, medium-grained, light-gray gabbro which in thin section is represented by No. 56 of the table. Still another facies consists of fine-grained, highly foliated, alternating bands of practically pure white plagioclase and gray gabbro, these bands varying in width from one-tenth of an inch to an inch or two. No. 58 of the table gives the minerals contained in a thin section of this third facies.

An important feature, excluding the dikes below described, is the close association of facies very different in composition. In some cases such facies are asymmetrically arranged, but more commonly they are in the form of more or less well-defined belts of zones which in some cases show fairly sharp boundaries, though they mostly grade into the adjacent facies. Such belts or zones commonly vary from a fraction of an inch to some yards or rods wide. The general effect is more or less well-defined local banded structures within the body of anorthosite-gabbro, especially in its northern portion. (See Fig. 2.)

VARIATIONS IN FOLIATION

Many portions of the anorthosite-gabbro, especially toward the north, exhibit more or less well-defined foliation. The greatest bulk of the rock is, however, practically devoid of such a structure. The non-foliated rock is mostly true gabbro, varying from light gray to very dark gray in color, medium grained to moderately coarse grained, generally with an ophitic texture. Some of the light-gray anorthosite-gabbro and anorthosite facies are also non-foliated. In many parts of the whole area there are gradations from facies which exhibit little foliation to others which are very highly foliated. As in the case of the variations in composition, so here the variations in degree of foliation generally occur as more or less well-defined belts or zones. Such belts commonly range in width from a few inches to some yards or rods. Highly foliated, moderately foliated, and non-foliated belts may lie adjacent to each other, in some cases with fairly sharp contacts, and in many cases with gradations from one into another. The variations in foliation are best exhibited in the northern portion of the area. In certain cases dark facies of the gabbro are so highly foliated that they look like hornblende schists. In other cases the rocks look like typical basic gneisses with alternating light and dark bands. Most of the anorthosite or gabbro shows moderate foliation due to a crudely parallel arrangement of the minerals, especially the dark minerals, without producing a banded effect. Figure 2 gives a fair idea of the variations in composition and foliation in a single small ledge.

An important feature of the foliation is the notable variation in strike within the body of anorthosite-gabbro. Ranges in strike

FIG. 2.—An exposure of anorthosite-gabbro showing notable local variations in composition and foliation. Just north of the northern road across the area.

FIG. 3.—White dikes rich in plagioclase and scapolite cutting anorthosite-gabbro, one-third of a mile south-southeast of the northern road.

from northeast to northwest have been observed. Notable variations also occur within relatively short distances, even within a few yards or rods.

VARIATIONS IN TEXTURE

As already stated, most of the rock, except toward the north, is a true gabbro varying from gray to very dark gray, the latter predominating. Such gabbro is medium grained to coarse grained, and it commonly possesses a fair to excellent ophitic texture. In the northern portion of the area most of the rock is a gray to light-gray, medium-grained to moderately coarse-grained anorthosite-gabbro varying to anorthosite which does not so commonly possess an ophitic texture. Local zones of light- to dark-gray anorthosite-gabbro and gabbro throughout the area are fine grained to medium grained and generally more or less highly foliated. In some local portions of the general mass almost perfectly euhedral crystals of plagioclase up to an inch long are set in a fine, granular groundmass of hornblende and monoclinic pyroxene.

The great bulk of the dark-gray gabbro shows little or no granulation. The very light-gray anorthositic facies are commonly considerably granulated. Much of the white feldspar of the light-gray anorthosite-gabbro, especially in the northern portion of the area, shows more or less granulation. Non-foliated facies of the light-gray anorthositic gabbro exhibit little or no granulation of the dark minerals, but not uncommonly in the foliated facies the dark minerals as well as the feldspar are granulated.

CAUSES OF THE VARIATIONS IN COMPOSITION, STRUCTURE, AND TEXTURE

It is believed that most, if not all, of the foregoing variations in composition, structure, and texture are primary features, in other words, that they developed under conditions of moderate pressure before or during the final consolidation of the anorthosite-gabbro magma. The main principles involved in the development of such features have been set forth by the writer in several recent papers[1] dealing with the origin of the foliation and banding of both the anorthosite and syenite-granite series of the Adirondack region.

[1] W. J. Miller, *Jour. Geol.*, Vol. XXIV (1916), pp. 600–619; *Science*, N.S., Vol. XLVIII (1918), pp. 560–63; *Bull. Geol. Soc. Amer.*, Vol. XXIX (1918), pp. 399–462.

A brief statement of the writer's explanation of the origin of the variations in composition, structure, and texture of the anorthosite-gabbro body will now be given.

1. It is believed that the intrusion of the anorthosite-gabbro magma was a complicated process of considerable duration. Much of the magma slowly solidified as a normal, moderately coarse-grained to medium-grained gabbro with an ophitic texture. Magmatic currents were practically absent from those portions.

2. In portions of the magma there were currents or movements sufficiently strong to cause the minerals, especially the earlier crystallized ones, to be drawn out into more or less perfect parallelism. This accounts for the gneissoid structure or foliation of considerable portions of the gabbro and anorthosite-gabbro, especially the medium-grained and fine-grained portions.

3. The more or less highly foliated structures of the many localized zones or belts of medium-grained to fine-grained rocks resulted from particularly active currents in those zones.

4. The more or less sharp alternations or variations in degree of foliation, and the notably varying strikes of the foliation throughout the area, are best explained as a result of locally developed differential magmatic movements or currents under conditions of not more than very moderate pressure. It seems impossible to account for such structures on the basis of pressure applied upon the body of anorthosite-gabbro after its final consolidation, first, because such pressure could not have caused notable foliation of certain narrow belts while adjacent masses were unaffected, especially in view of the fact that the highly foliated zones are not characterized by shearing or crushing (granulation), and, second, because any such pressure sufficiently strong to produce foliation must have been exerted in a single general direction with about equal force, and hence the sharp variations in strike of the foliation are left unaccounted for.

5. The variations in composition are the result of differentiation of the anorthosite-gabbro magma before or during its consolidation.

6. Those foliated zones or belts which show sharp variations in composition in layers ranging from nearly pure plagioclase to gabbro rich in ferro-magnesian minerals are the result either of

differentiation into such layers, probably accompanied by differential movements, during the intrusion, or of local intrusions of heterogeneous portions of the magma in which the differentiation took place before intrusion along local zones.

7. Certain local dikelike facies extra rich in ferromagnesian minerals, which are not sharply separated from the main mass of the anorthosite-gabbro and send dikelets into it, are basic differentiates from a lower level forced upward into the more normal mass which had already more nearly approached final consolidation.

8. The granulation of the feldspars in those portions of the foliated lighter-gray gabbro and anorthosite-gabbro in which the ferromagnesian minerals show little or no granulation is believed to have resulted mainly from movements in the magma before final consolidation, that is during or after the crystallization of the feldspars, but while the ferromagnesian minerals were still more or less liquid. In other words, we are here dealing with a protoclastic texture. Such pressure could not have been applied after complete consolidation of the magma because, if so, the dark minerals would also be granulated. Where the ferromagnesian minerals also show granulation, this probably resulted from magmatic movements just prior to final solidification, or from pressure upon solidified portions of the mass exerted by locally intruding portions of still liquid rock. The possibility is conceded, however, of the development of some granulation of this type by external application of moderate pressure upon the whole body of anorthosite-gabbro, but the localization of such granulation renders such an explanation less likely.

DARK DIKES RICH IN HORNBLENDE AND SCAPOLITE

At locality 7 there is a fine display of rather remarkable dikes. The country rock is there mainly a medium-grained, dark-gray, rather typical, non-foliated gabbro with ophitic texture. No. 51 of the table gives the mineral content of a thin section.

Over an area of several acres the rock just described is cut most irregularly by a network of numerous dikes of dark-gray, highly foliated, fine-grained to medium-grained rocks consisting chiefly of scapolite and hornblende together with some quartz and

magnetite and a little pyrite. No. 52 of the table shows the simple but rather remarkable mineral content of a thin section of one of these dikes. The scapolite is clear and fresh in the form of irregular grains. The hornblende is the common variety with pleochroism ranging from dark green to greenish yellow. Nearly all the minerals are distinctly elongated parallel to the foliation. There seems to be no granulation. These dikes have more or less indefinite boundaries against the normal gabbro into which they fray out most irregularly. They seldom exceed a foot in width. The highly foliated structure of dikes arranged like these in normal gabbro cannot have resulted from pressure brought to bear upon the whole mass of rock after it had all become consolidated. It is evident that we are here dealing with a remarkable case of primary foliation developed to a high degree in small dikes before their final consolidation. The lack of sharp contacts points to the intrusion of the dike material into the gabbro while the latter was still hot, though nearly or quite consolidated.

In the light-gray anorthosite-gabbro of the northern portion of the area, some dark, hornblende-rich, well-foliated dikelike bands occur. In some cases the contacts are fairly sharp, and in others they are not. Most of these bands quite certainly represent intrusions into the still hot but nearly or quite solidified country rock, and their foliation is of primary origin. None of these bands show a network arrangement. Whether or not they, too, are rich in scapolite is not known.

WHITE DIKES RICH IN PLAGIOCLASE AND SCAPOLITE

At a number of localities white dikes were observed to cut the anorthosite-gabbro and gabbro. A good display of such dikes may be seen in a ledge at locality 5 (see Fig. 3). The main rock of the ledge is gray, medium-grained, well-foliated gabbro varying to anorthosite-gabbro. Several white dikes ranging in width from one to several inches cut across the foliation of the gabbro at high angles. These dikes, which are roughly parallel and traceable for a rod or more, contain a maximum of not more than a few per cent of dark minerals. They are fine grained with some scattering feldspars up to one-half an inch in length. Contacts against the

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country rock are not very sharp. No. 49 of the table gives the mineral content of a thin section of the dike rock. Little or no granulation is shown. The scapolite, which is very clear and fresh, occurs mostly in the form of irregular grains as inclusions in the feldspar. Since the scapolite grains are variously oriented in the feldspar and their contacts are sharp, it is evident not only that the scapolite crystallized before the plagioclase, but also that it is not merely a decomposition product of the feldspar. Either the scapolite is of primary origin, or it somehow represents recrystallized material.

On a little hill at locality 10 several similar dikes were observed. Some of these show a moderate degree of foliation. Others occur here and there in the anorthosite-gabbro at localities 6, 7, 11, 12, and 13. Still others fill many of the cracks in the prominent zone of fractured and crushed anorthosite-gabbro described below.

On the one hand, the true dike character of these white rocks and their strike across the foliation of the country rock at high angles prove that they were intruded after the anorthosite-gabbro, which contains them, had almost or completely solidified. On the other hand, their lack of sharp contacts indicates that they were intruded while the anorthosite-gabbro was still hot enough to allow some merging of the dike materials with the walls. The dike material probably originated by differentiation in a still more or less liquid portion at a lower level and was then forced into fissures in a higher, cooler portion of the anorthosite-gabbro body.

The dikes are, according to this view, satellitic dikes of the anorthosite-gabbro.

HORNBLENDITE DIKES

These are remarkable dikes consisting of pure hornblende. Altogether in the northern one-third of the area of anorthosite-gabbro many dozens of the hornblendite dikes were observed. They are generally grouped in certain portions of the anorthosite-gabbro where it has been fractured. At locality 10 many cracks, commonly in the form of a network in the light-gray, moderately coarse-grained, little foliated gabbro, are filled with small dikes of moderately coarse-grained pure hornblende. Contacts of the

dikes are not sharp. At locality 5, close to the white dikes shown in Figure 3, the anorthosite-gabbro contains many roughly parallel

FIG. 4.—Dikes of hornblendite filling curving cracks in anorthosite-gabbro, one-third of a mile south-southeast of the northern road.

FIG. 5.—Ledge of granite containing curving cracks filled with pyroxenite dikes on the left side, and nearly vertical cracks filled with pyroxene-rich pegmatite dikes on the right side. Close to the very northern end of the anorthosite-gabbro area.

curving cracks filled with small dikes of pure hornblendite (see Fig. 4). Still farther south, especially at localities 7, 11, 12, and 13, more cracks are filled with hornblendite dikes.

The hornblendite dikes are commonly from one-half an inch to one inch wide, and they are seldom traceable individually for more than a few yards or rods. They cut the anorthosite-gabbro in all directions, not uncommonly at high angles across its foliation. Contacts against the country rock are always sharp. The dike material is practically pure, common hornblende which, in the hand specimen, is greenish black where fresh, and dull green where weathered. The dikes are rather uniformly moderately coarse grained, the crystals usually varying in length from one-fifth of an inch to one inch. There is no suggestion of finer grain along the borders. Granulation is absent.

Many of the dikes occupy curving cracks in the anorthosite-gabbro as described below. In some such cases hornblendite dikes lie in rather sharp contact against dikes of nearly pure plagioclase anorthosite. On the southern face of the little hill at locality 10, several hornblendite dikes cut sharply across some branching, white, plagioclase-scapolite dikes, the latter in some cases being faulted where the hornblendite dikes cross.

Both the hornblendite dikes and the white dikes rich in plagioclase and scapolite are quite certainly late differentiates of the cooling anorthosite-gabbro magma at some depth below the present rock surface. They are in a real sense complementary dikes, the differentiated white-dike material having been forced upward into the nearly or quite consolidated, but still hot, anorthosite-gabbro, while the differentiated hornblendite was later forced upward into cracks in the relatively much cooler body of anorthosite-gabbro. This is in harmony with the lack of sharp contacts of the white dikes, and the sharpness of contacts of the hornblendite dikes.

In the discussion of this paper at the Boston meeting of the Geological Society, N. L. Bowen suggested that the fissures filled with hornblende might better be called veins instead of dikes. But, because they show no vein structure and are in almost every way like true dikes, the writer considers them to be dikes, probably in the category of pegmatites because of their coarseness of grain and lack of chilled borders. It is accordingly reasonable to believe that the hornblende was either in solution in a pegmatite

residue of the anorthosite-gabbro magma, or it was taken into solution by magmatic solvents during their passage through the anorthosite-gabbro after it was nearly or wholly consolidated but still hot. That the general rock mass was still hot during the intrusion of the hornblendite dikes is proved by the fact that still later minor intrusions, as distinct facies of the anorthosite-gabbro, took place. In any case we are dealing with magmatic intrusive material (hornblendite) which should be classed as dike rather than vein material.

FRACTURED AND CRUSHED ZONES

A remarkable zone or belt of fractured, and in part crushed, anorthosite-gabbro occurs near the northern end of the area. It strikes about north 60° west and extends partly across the northern road near the granite contact at locality 2. This fractured zone maintains a fairly uniform width of about one rod, and it is very clearly exposed across a great ledge of bare rock for approximately two hundred feet on the north side of the road. South of the road it shows much less. The main body of rock of this zone varies from nearly white anorthosite to light-gray anorthosite-gabbro. This zone is characterized throughout its length by a remarkable system of curving, roughly parallel cracks. In a sense the cracks are festooned one within the other. This system of cracks extends across the zone of fracturing rather than parallel with it. Fig. 6 gives a fairly good idea of the structure, though the foreshortening in the picture is strong. The description immediately following pertains to this photographed locality twelve or fifteen rods north of the road. Between the cracks the distances generally range from one to six or eight inches. Most of the cracks (now filled) are from one-fourth of an inch to two inches wide, but they vary considerably even within a few inches. A single crack is seldom traceable for more than five or six feet. The cracks are filled chiefly with rather fine-grained, nearly pure-white, plagioclase-rich material. The walls of the cracks are mostly exceedingly irregular, with multitudes of sharp indentations, usually less than an inch deep, into which the feldspar has been filled. In many cases the plagioclase-rich filling sends off small tongues or dikelets, rarely over a foot long, ending in fairly sharp points in the anorthosite-gabbro. Some of the filled cracks are

distinctly lenslike, up to a foot long. That the plagioclase-rich material was forced into the cracks in the form of dikes seems

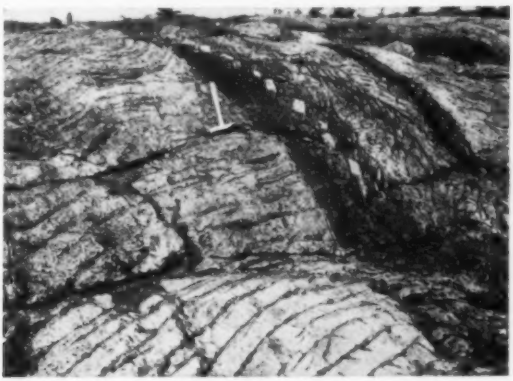

FIG. 6.—A portion of the remarkably fractured zone of anorthosite-gabbro with its dikes in the northern portion of the area. About fifteen rods north of the northern road.

FIG. 7.—A local highly crushed portion of the prominent zone of fracturing in the anorthosite-gabbro. A few rods north of the northern road.

almost certain. Contacts of the dikes against the anorthosite-gabbro are generally fairly sharp. On the north side of the photographed locality (see left side of Fig. 6) a good many very small

dikes of hornblendite occur within the dikes of white plagioclase-rich material. These dikes of hornblendite are exactly like the ones above described. Lying in the midst of the fractured zone at this locality and parallel to its strike, there is a twenty-inch wide band of dark, highly foliated gabbro rich in ferromagnesian minerals (see Fig. 6). This band of dark gabbro cuts squarely across the curving, dike-filled cracks by sharp contact on one side and by moderately sharp contact on the other side. In the midst of the dark band and parallel to it there is a dikelike strip of white plagioclase-rich anorthosite several inches wide, separated into blocks by multiple faulting. These faults extend across the dike-filled fractures of the anorthosite-gabbro on one side. The dark band of gabbro with its faulted white strip is well shown in Figure 6.

The history of the features which occur at the locality just described is probably about as follows. The main mass of the anorthosite-gabbro now at the surface was intruded and nearly or completely solidified. Then it was subjected to a torsional strain, probably due to a moderate pressure externally applied, whereby the system of parallel curving cracks was developed. The cracks were filled with plagioclase-rich dike material forced upward as a differentiate from a lower level of still more or less liquid gabbro. Still later came the intrusion of the hornblendite dikes into some of the same cracks, this material also having been produced as a differentiate at a lower level. Distinctly later, the twenty-inch-wide band of dark gabbro rich in ferromagnesian minerals was intruded, this material also having been derived from a portion of the general gabbro mass which was still in a more or less liquid condition at a lower level. Then the small white dike was intruded into the band of dark gabbro. Finally, after the whole complicated mass of gabbro and anorthosite now at the surface was solidified, the band of dark gabbro with its small white dike and the adjacent rock on one side were subjected to multiple faulting on a small scale.

A local portion of the fractured zone lying a few rods north of the road exhibits a high degree of crushing. Figure 7 gives a fair idea of this locality. The rock is mostly a very light-gray

to nearly white anorthosite relatively free from dark minerals. The ledge contains thousands of rounded to subangular pieces of medium to coarse granular plagioclase-rich material imbedded in a matrix of distinctly finer-grained groundmass. Remnants of the system of parallel curving cracks are clearly visible in parts of the ledge as, for example, just above the hammer in the picture (Fig. 7). Evidently here, as well as in that part of the ledge farther west, the system of crudely parallel curving cracks was developed by moderate pressure (probably a torsional strain) after the magma was nearly or completely solidified, but under continued pressure the rock was mostly shattered into small fragments. It seems likely that considerable nearly pure anorthosite magma then invaded the shattered mass and that the rounding off of the fragments was probably partly due to the mechanical crushing and partly to magmatic corrosion.

Certain other portions of the anorthosite-gabbro also show multiple fracturing but on lesser scales as, for example, at localities 5, 7, and 12.

PEGMATITE DIKE RICH IN PYROXENE

A pegmatite dike of special interest occurs in the anorthosite-gabbro at locality 3. It cuts across the foliation of the gabbro in the form of a lens with a length of twenty-five feet and a maximum width of three feet. It sends off one distinct branch about a yard long into the gabbro. This dike consists mostly of feldspar (chiefly oligoclase) and green monoclinic pyroxene, together with 5 to 8 per cent of quartz, all in anhedral crystals commonly from one to several inches long. Nearly all the pyroxene occurs in very irregular segregation masses up to several feet across. Some of the quartz is associated with plagioclase, and some occurs within the pyroxene segregation masses. This dike lies in sharp contact against the anorthosite-gabbro except within a few feet of each end.

This pegmatite is believed to be an offshoot from the adjacent granite, the magma or magmatic juices of which, on their way through the gabbro, dissolved or digested materials (chiefly ferromagnesian) from the gabbro, thus giving rise to the rather basic pyroxene-rich pegmatite. Because of the dissolving power of the

pegmatitic juices of magma, sharp contacts against the country rock would not be expected except where the magma had risen far enough to have lost its dissolving power. Further light is thrown upon the problem of the origin of this pegmatite rich in pyroxene in the discussion of the pyroxenite dikes (see below) which occur in the adjacent granite.

PYROXENITE DIKES IN THE ASSOCIATED GRANITE

Near the very northern end of the area of anorthosite-gabbro (locality 4), pyroxene-rich dikes cut a ledge of medium-grained, well-foliated, moderately hornblendic, pink granite close to its contact with the gabbro. Figure 5 shows the general relationships. On the left side curving parallel cracks in the granite are filled with dikes of pure to nearly pure, moderately coarse-grained, dark-green monoclinic pyroxene (apparently common augite). They contain only a few scattering crystals of orthoclase and quartz. None of these dikes is over an inch in width, and they all pinch out in the granite. Seven of them, up to two yards long, are perfectly arranged as a curved series one above the other in the face of the ledge. They show sharp contacts, and they cut across the foliation of the granite at high angles. On the right side (see Fig. 5) there are five or six coarser, crudely parallel, nearly vertical dikes, up to several inches each in width, in sharp contact with the granite. Crystals range up to two inches across. These dikes contain scattering crystals of orthoclase and quartz, but never more than 10 per cent. Between the two sets of dikes just described there is an irregular mass of very coarse pegmatite with crystals of quartz, orthoclase, and pyroxene up to six inches in length, but here the pyroxene is subordinate in amount. This mass shows only moderately sharp contacts against the granite.

It seems most probable that the pyroxene of both the pure pyroxene and pyroxene-rich pegmatite dikes was derived from the anorthosite-gabbro. Where the magma or juices passed through the gabbro, the pyroxene is believed to represent dissolved or digested and recrystallized ferromagnesian material.

It is important to bear in mind that the dikes of pure pyroxenite, as well as the dikes of hornblendite above described, are examples

of almost perfect mono-mineralic dikes. The pyroxenite dikes quite certainly, and the hornblendite dikes most probably, are of pegmatitic, magmatic origin, the magmatic solvent or solvents (probably largely water) having disappeared during the crystallization. In conclusion it is suggested that mono-mineralic dikes like the pyroxenite and hornblendite above described should not necessarily, as Bowen[1] reasons, be excluded from the category of intrusive rocks. Is it not true that all active magmas are more or less rich in mineralizers, and is it not further an open question as to whether any magma can remain active, that is, still possess an intrusive power, after its mineralizers have all disappeared? Pegmatitic magmas of relatively early origin in their parent-rock are probably such powerful agents of intrusion and even of injection because of their richness in mineralizers. Does not the argument that no rock consisting of but one mineral could ever have existed as an intrusive magma, because at least one mineral must act as a solvent and another as a solute, disregard the perfectly plausible possibility of a single substance dissolved in some solvent which itself may not crystallize along with the dissolved material?

[1] N. L. Bowen, *Jour. Geol.*, Vol. XXV (1917), pp. 218, 235–36, 242–43.

A NEW FORM OF *DIPLOCAULUS*

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To all who have worked with the genus *Diplocaulus*, the great variety in the shape of the skull and the peculiarities in other parts of the skeleton are known. Even after the analysis of the group by Case, Williston, Douthitt, and others the several species assigned to the genus are not entirely satisfactorily defined and there are many details of the anatomy still to be determined.

Recently, through the courtesy of Professor R. D. Salisbury and with the assistance of Mr. Paul C. Miller, the writer was permitted to examine the many specimens of *Diplocaulus* in Walker Museum, the University of Chicago. Among the materials is a recently discovered specimen which, because of its distinctness from described forms and the possible light it throws on the development of the Diplocaulian characteristics, is worthy of description.

Diplocaulus primigenius SP. NOV.

The material herein described consists of a large skull of the type designated by Case[1] as *D. magnicornis*, nine dorsal vertebrae, seven ribs, and a fragment that the writer takes to be a part of the right clavicle. All these parts are well preserved and have been skilfully prepared and mounted on a plaster base by Mr. Miller.

When found the vertebrae formed a curved, but unbroken series extending back from near the posterior border of the skull. At least one of the anterior vertebrae is missing. The ribs lay in an orderly pile to one side of the vertebrae.

THE SKULL

While the skull is essentially complete, its state of preservation prevents a detailed description of its characteristics. Little or

[1] E. C. Case, "Revision of the Amphibia and Pisces of the Permian of North America," *Carnegie Inst. of Washington, Publication No. 146*, (1911), p.21.

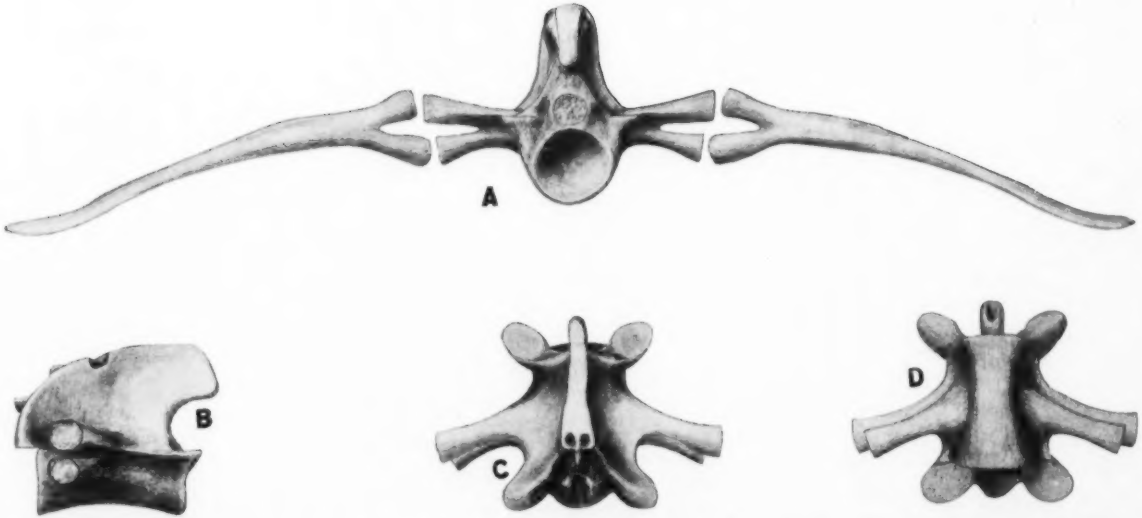

FIG. 1.—*Diplocaulus primigenius: A*, anterior view of sixth(?) vertebra with ribs attached; *B*, *C*, and *D*, the same vertebra from the right side, from above, and from below. All figures slightly under $\frac{2}{3}$ natural size.

nothing can be determined concerning those points bearing on the less well-established relations of the various elements. The palate surface has been crushed and lost in part and only the proximal end of the right ramus of the lower jaw is preserved.

A few sutures can be definitely determined, chiefly those of the dorsal surface back of the orbits. In these no departure from the arrangement as shown by Douthitt[1] is noted, but the doubtful portion about the orbits and nares can be neither verified nor disproved. In its general appearance there is nothing to distinguish this skull from any other of a dozen that have been referred to *D. magnicornis*. Although the posterolateral horns are broken off near the tips they are undoubtedly of the bluntly pointed, non-curved variety. The posterior border of the skull is broadly

FIG. 2.—*Diplocaulus primigenius:* scapular process of right clavicle from the inner side. Natural size.

concave. None of the details such as the forward extent of the frontal and the arrangement of the vomerine teeth as stressed by Case[2] can be determined. The sculpture of the facial region is decidedly not radial.

The length of the skull along the median line is 116 mm. The tabular horns project back from the posterior border of the skull at the median line a distance of 78 mm. and extend 338 mm. from tip to tip.

The borders of the orbits are largely restored, but the indications are that these openings were above the average in size, possibly as much as 17 mm. or more in diameter.

The possibility of a gill chamber beneath the broad base of the posterolateral horns has been pointed out by Williston, Douthitt, and others. The notch made by the more or less abrupt ending of the

[1] Herman Douthitt, "The Structure and Relationships of *Diplocaulus*," *Contributions from Walker Museum*, Vol. II, No. 1 (1917).

[2] *Op. cit.*, p. 21.

quadratojugal near the mid-length of the horns on their underside apparently forms the anterior border of an opening for the entrance of water into the gill chamber. In most *Diplocaulus* skulls there is a depressed area along the quadratojugal-squamosal union which increases in depth toward the notch, possibly to direct water into the opening. In the specimen herein described the notch is unusually pronounced and the depression leading to it is longer, deeper, and more nearly smooth than is commonly noted.

THE VERTEBRAE

The real interest in the material centers in the vertebrae, especially in their exceptionally large size and in the development of the neural spines. While there is no means of determining accurately the position of the series in the vertebral column, it is assumed that they are from the anterior end, very likely numbers 3 to 11. The first of the preserved series is somewhat shorter than any that follow and it alone has a conspicuous lateral expansion of the neural spine, a condition that suggests its proximity to the skull. Furthermore, this vertebra is the only one of the series that lacks the characteristic pit in the top of the spine, a feature more or less well developed in all the anterior vertebrae except in numbers 1 and 3 in several specimens of the described types examined by the writer.

The string of nine connected vertebrae measures about 354 mm. While this length is made up in a small part of matrix separating the centra, the figure serves well for comparison of this with previously described forms of *Diplocaulus*. The average length of a like number of vertebrae from the same region of the column in several specimens in Walker Museum is but little more than half that given above. All other dimensions of the vertebrae herein described are correspondingly large. So striking is the size that were it not for the fact that in nearly every other detail the vertebrae are those of the typical *Diplocaulus* there might be some doubt as to their identity.

In length the centra increase from about 25 mm. at the anterior end of the series to 40 mm. at the posterior end. The greatest increase is between the first and second, an increase of 5 mm.

The lower side of the centrum is markedly concave anteroposteriorly and distinctly convex from side to side at mid-length.

The diapophysis is somewhat longer than the parapophysis. Both arise from about the mid-length of the vertebrae, the former from the arch and the latter from the centrum. They are united for a short distance at their base. Both increase in diameter toward the distal end where they are distinctly enlarged.

In the described forms of *Diplocaulus* the neural spine has but little development. It is usually little more than a sharp, ridgelike thickening of the arch over the neural canal. In the vertebrae herein described one of the most conspicuous features is the spine development. For the most part the spines are comparatively high with flat, more or less rugose tops. The first of the series is distinctly expanded laterally at its top. It is only in the last two of the series that there is a suggestion of the sharp, keel-like degeneracy of the spine and even in these two vertebrae it rises distinctly above the arch. The ratio between the portion below and above the plane of the zygopophyses throughout most of the column is 4:7 while in the average previously known form the ratio is 4:4. In the last two vertebrae of the present specimen the ratio is about 4:5.

One of the characteristic features of the vertebrae of *Diplocaulus* is the presence of a pitlike depression on the top of the spine. There is a great variety in this pit development ranging from very small, round openings to rather pronounced, laterally elongate depressions. In one string of eleven connected vertebrae, No. 1016 in the Walker Museum Collections, the pits seem to be entirely lacking in all back of the fifth. The first pit is in the second vertebra in every case. Usually it is very conspicuous and more or less quadrangular in shape. The third vertebra apparently lacks the pit. In the following vertebrae the number with pits probably varies from individual to individual. For the most part there is no suggestion of an anteroposterior constriction or division of the pit into two distinct facets and in no specimen except the one herein described has the writer seen distinctly double pitting. In the present specimen, however, in each vertebra except the first of the preserved series which is pitless, the spine depressions are

distinctly paired. In most cases the depressions are connected by a very shallow and narrow groove, but in one or two of the vertebrae the openings are distinct. The size of the pits is another distinctive feature of this form. Between the lateral margins of the pits of the fourth vertebra is a distance of 7 mm. and in every case the pits are so large and so widely separated that the spine is distinctly swollen for their accommodation. Clearly, whatever the function of these pits it was more fully exercised in this than in any of the other forms that have been observed.

As in the typical *Diplocaulus*, the articular faces of the zygopophyses are directed straight up and down so that their common plane furnishes a plane of reference for describing proportions. The zygosphene and zygantrum is strongly developed throughout the series of vertebrae. Posteriorly the neural spine divides to send strong buttresses down, out, and back to the posterior zygopophysis. Between these buttresses there extends back in a horizontal plane a spoutlike projection, the zygantrum. The spine of the preceding vertebra extends forward as a vertical plate running in the groove or spoutlike zygantrum without any noticeable modification for the articulation. There is a suggestion of further strengthening of the intervertebral articulation through a more or less pronounced vertical keel between the posterior, zygopophysial lamellae at the anterior end of the zygantrum excavation. Some of the vertebrae show a corresponding excavation on the lower anterior edge of the zygosphene extension of the spine.

The following table comparing the various dimensions of the present specimen with those of the common type, No. 1018 in the Walker Museum Collections, will serve to emphasize the differences.

	W.M. No. 564	W.M. No. 1018
	mm.	mm.
Length of centrum	40	22
Dist. across transverse processes	70	44
Greatest height	40	23
Below plane of zygo	14	12
Above plane of zygo	26	11
Across zygopophyses	36	21

THE RIBS

Of the ribs preserved none resembles the comparatively short, straight, distally expanded form figured by Douthitt[1] in the neck region of his skeletal restoration, and commonly found in the large collections of *Diplocaulus* material. It is entirely possible that none of the typical anterior ribs were preserved. Those present were in a more or less connected pile and not directly articulated with the vertebrae. It is assumed, however, that they belong near the anterior end of the preserved string of vertebrae where they were found, and represent a more primitive stage in the development of *Diplocaulus*. Their exceptional curvature and length are at once striking. Only one is preserved in its entire length. This measures 111 mm. Some of the other ribs were evidently shorter than this but for the most part they indicate an equal or even greater length.

In the one complete rib there is a departure from a straight line of 20 mm., perhaps the average. Some are more sharply curved and others less. The distal half is essentially straight, the curvature being a gradual bending of the proximal half. The curvature is within a plane that departs little from the horizontal so that a body cross-section shows but a slight down-bending of the ribs, a condition entirely in keeping with the generally accepted conception of a broad, flat, bottom-living type. The capitulum and tubercle are both markedly expanded and undoubtedly formed a firm attachment of rib to vertebrae.

HABITS AND RELATIONSHIPS

The aquatic adaptations of *Diplocaulus* have been repeatedly pointed out by various writers. In typical forms there is much evidence that these amphibians were of the groveling, bottom-living type. So bizarre are the skull modifications and body form and so obscure are the stages leading up to this condition that any suggestions are of exceptional interest.

In several respects the form herein described seems to represent an antecedent step in *Diplocaulus* evolution. At least it offers some pointed suggestions as to the several stages through which

[1] *Op. cit.*

the group passed. The large, strong vertebrae; the well-developed spines, and the highly curved ribs approach the normal condition of the more generalized Stegoceph. The well-developed zygosphene and zygantrum articulations bespeak a strength and flexibility of the vertebra column such as belongs to a creature that has developed swift progression through the water by means of tail propulsion.

The remarkable pit development on the spines of this form suggests a still further step in its modifications for swift movement through the water. It seems highly probable that the pits formed an articulation for anteroposteriorly movable spines that gave support to a dorso-median fin. The lateral rigidity of such a fin was assured by the double articulation indicated by the well-developed double pits. As would be expected, the anterior fin spine gives evidence of its superior size and strength of articulation through the very conspicuously larger pit on the second spine. The present specimen lacks the first vertebra, but the several strings of previously known forms examined by the writer establish this point. In the backward folding of the fin spines extra space would be required behind the enlarged anterior spine. Perhaps this accounts for the uniform absence of the pit or pits in the third vertebra.

Not entirely in keeping with these swift-swimming modifications is the remarkable development of the shoulder girdle. The fragment that the writer identifies as the ascending process of the right clavicle is stout and something over 60 mm. long. It is strongly grooved on the outer-posterior side for articulation with the scapula. In all figured specimens of *Diplocaulus* and the many other specimens examined by the writer this process is short. In some cases it may have been broken off but after making due allowances for this it does not seem likely that there was an actual articulation with the scapula or at best, but a weak one. Perhaps the ancestral *Diplocaulus* was a creature that had become well adapted to swift progression through the water to the extent of a suitable vertebral evolution and the reduction of the limbs. At a later stage this actively swimming form likely degenerated to the groveling type in which habitat the girdles continued to reduce

in size and strength of attachment and the vertebral column lost much of its vertical rigidity through the reduction of the spines. Naturally the supports for the dorso-median fin degenerated to a smaller size and a single articular facet. Very likely in the process of flattening the body, one of the first steps was the backward twisting of the curved ribs, a stage preserved in the present specimen, and a later tendency toward straight ribs.

Of the distinctness of this form there can be no question. True, the skull differs very little from many described forms. Greater variations are undoubtedly rightly included in a single species. One might logically expect that the remarkable modifications should reach the skull and limbs before the vertebral column. While all indications are that the skull and associated vertebrae are of the same individual there is, nevertheless, a possibility that the association is of two widely differing species. For this reason the vertebrae and long, curved ribs are considered typical of the new form which the writer wishes to designate as *Diplocaulus primigenius*.

The material on which this form is based is No. 564 of the Walker Museum Vertebrate Collections in the University of Chicago. It was found by Mr. P. C. Miller in Baylor County, Texas, on Brush Creek near Seymour.

The writer takes this opportunity to express his appreciation of the kindness of Professor Salisbury in permitting the study of this material and for the courtesies shown by Mr. P. C. Miller, whose skill and painstaking care in preparing the bones have made it available.

A GLACIAL GRAVEL SEAM IN LIMESTONE AT RIPON, WISCONSIN[1]

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University of Wisconsin

Just west of the city of Ripon (S.E. $\frac{1}{4}$ of N.W. $\frac{1}{4}$, Sec. 20, T. 16 N., R. 14 E.) is a limestone quarry belonging to Mr. William Kroll. This locality (Fig. 1) displays a phenomenon of unusual interest, namely, a seam and pockets of glacial gravel within the Paleozoic rocks.

In 1914 the writer visited this quarry in company with E. O. Ulrich, United States Geological Survey, W. O. Hotchkiss, state

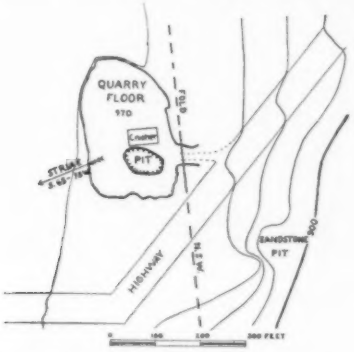

FIG. 1.—Sketch map of Ripon limestone quarry. Topography adapted from U.S. Geological Survey, contour interval 20 feet.

geologist of Wisconsin, and Edward Steidtmann. Further field work was done in 1915 in company with Lawrence Martin and Walter H. Schoewe, and in 1919. The writer is indebted to all of these persons for assistance, criticisms, and suggestions.[2]

[1] Published by permission of the state geologist of Wisconsin.

[2] Lawrence Martin, "The Physical Geography of Wisconsin," *Bull. 36, Wisconsin Geol. and Nat. Hist. Survey*, 1916, pp. 250–51.

A few rods east of the Kroll quarry, on the side of the hill which slopes to the east, is a pit in soft St. Peter sandstone which is overlain, at the top of the exposure, by a few feet of disintegrated Trenton dolomite. Within the sandstone are crevices and pockets filled with glacial gravel. Excavations at the bottom of the pit show the shaly and cherty zone characteristic of the top surface of the underlying Lower Magnesian formation which here dips about 30 degrees to the east.

In the Kroll quarry, on the hill to the west, 50 feet higher than the bottom of the pit, sandstone is seen at the entrance, overlain

FIG. 2.—Fold at entrance of Ripon limestone quarry, looking north

by a few feet of dolomite at about the same level as that to the east. At the eastern edge of the quarry proper is the monoclinal fold shown in Figure 2. The displacement is from 8 to 10 feet, down to the west, and the strike is N. 5° W. Less than 40 feet west of this fold is a pit in the main floor of the quarry 40 feet deep, which shows no St. Peter sandstone. The quarry well reaches sandstone at a depth of 100 feet (Fig. 3).

[1] In Figure 3, No. 1 is Lower Magnesian; Nos. 2 to 4 and 6 to 8, Trenton; and Nos. 5 and 9, Pleistocene; the sandstone in the well is Cambrian.

The gravel seam, No. 5, extends throughout the quarry, which is over 200 feet across. The dolomite layers above the seam are in no way unusual, but along the seam is considerable weathering so that the underlying rock is nearly everywhere disintegrated into a putty-like yellowish clay to a depth of an inch or two. It is this feature rather than the presence of gravel which makes this horizon so prominent, as is shown in Figure 2. The gravel

9. Glacial till	2–3 feet
8. Gray, thin bedded dolomite	5.0 feet
7. Bluish thin-bedded dolomite	4.5 feet
6. Grayish-blue dolomite	0.8 feet
5. Glacial sand and gravel maximum	0.2 feet
4. Hard gray rather thin-bedded dolomite	5.3 feet
3. Blue, heavier bedded dolomite with fossils; sandy at base	6.5 feet
2. Sandy buff dolomite, forming a parting	0.5 feet
1. Gray dolomite with layers of gray shale and sandstone. Irregular beds, the bedding in general dipping at low angles to the east	40.0 feet
Total, about	63 feet

FIG. 3.—Section of Kroll quarry, Ripon, Wis.

and sand layer is best developed in the eastern part of the quarry. In thickness, the sand and gravel layer varies from a mere trace up to a maximum of about two inches (Fig. 4). The largest pebbles are about an inch in diameter. Dolomite, granite, greenstone, and quartzite were distinguished. Minute cross-bedding is locally observed.

In the sandstone pit to the east, larger gravel deposits are found filling gashes or irregular openings in the rock. Some of the openings are as much as three feet across and of irregular shape.

As No. 1 of the section does not contain fossils, the correlation of this section with that seen in the sand pit to the east is somewhat puzzling, but the evidence of the rocks and fossils, of the sloping surface of the Lower Magnesian seen in the sandstone pit, and a close study of the supposed fault unite in definitely proving that the St. Peter pinches out in the interval. Statements of Mr. Kroll regarding exposures formerly visible in a trench through the quarry floor also confirm this explanation. Similar phenomena without the complicating presence of folding are known elsewhere in the vicinity.[1]

FIG. 4.—Close-up view of gravel seam, showing weathering of adjacent dolomite. (Photograph by W. O. Hotchkiss.)

Before considering the origin of the gravel seam, the question of the origin of the fold with which it is related may be considered. The fold might be due:

1. In some way to the pinching out of the St. Peter.

2. To glacial pressure on the east side of the hill, which forced up the wedge of St. Peter sandstone resting upon the sloping surface of the Lower Magnesian.

3. To the same processes which formed the major joints and the other faults and minor folds which are found in the Paleozoic rocks of eastern Wisconsin.

[1] T. C. Chamberlin, *Geology of Wisconsin*, Vol. II (1877), pp. 270–75.

The direction of the movement which caused the fold is not in harmony with slumping of the St. Peter on the inclined surface of the underlying Lower Magnesian. The hypothesis of slumping might, however, explain the eastward-dipping slips and gashes in the St. Peter sandstone.

The forcing up by glacial pressure of a wedge of St. Peter upon the shaly surface of the underlying Lower Magnesian is a satisfactory hypothesis. The strike of the fold is N. 5° W., that of the glacial striae on top of the quarry S. 65–75° W., making an angle of 70 to 80 degrees. Somewhat similar phenomena are described by Chamberlin near Burlington, Wisconsin, and by Alden.[1]

Folds are known in the Paleozoic rocks of the region, as at the abandoned quarry in Fond du Lac, while faults are by no means uncommon. In many instances it can be definitely proved that these features far antedate the glacial period and are not due to ice work. It is therefore necessary to have more evidence than is now at hand to prove that these particular joints and folds at Ripon are different in age from those of the Driftless Area. The localization of the fold by the wedging out of the sandstone will fit with this hypothesis as well as that of glacial pressure.

The writer has therefore concluded that the fold is probably only in part due to glacial action but was principally caused by earth movements.

The following hypotheses may be considered in connection with the origin of the gravel seam between the dolomite layers:

1. Deposition of gravel in Ordovician times between layers of dolomite.

2. Glacial transportation of a slab of dolomite on to a previously planed-off surface, covering a small thickness of gravel.

3. Raising of frozen-together upper layers, possibly during the formation of the fold, followed by filling of the crack with gravel and subsequent settling back of the overlying rocks.

4. Entry of glacial or post-glacial gravel-bearing waters along a bedding plane.

[1] T. C. Chamberlin, *Geology of Wisconsin*, Vol. II (1877), p. 203; Wm. C. Alden, "Quaternary Geology of Southeastern Wisconsin," *U. S. Geol. Survey, Prof. Paper 106* (1918), pp. 206–8.

The absence of similar deposits of proved Ordovician age, together with the lack of induration and the presence of the gravel-filled gashes in the sandstone, definitely eliminate the first hypothesis.

The second theory may be divided into three subdivisions: (*a*) distant source for the dolomite slab; (*b*) movement by rotation without transportation to any great distance; (*c*) slight lateral movement causing the opening of an irregular bedding plane by destroying the registry of the irregularities.

a) No nearby source for such a gigantic slab (at least two hundred feet square) can be found except on the hill northwest of the quarry, and a glacial movement from the northwest is impossible since the Driftless Area is not very far away in that direction. The glacial transportation without breaking of such an enormous piece of rock for any distance, as from across the valley to the east, is quite out of the question. The rock above the gravel seam is no more broken than is usual near the surface of the ground. The major joints, which strike from N. 5° W. to N. 30° W. pass right through the gravel seam (Figs. 5 and 6) and there seems no valid reason to assign a glacial or post-glacial age to them. In fact, there is no difference in the rocks above from those below the seam and no glacial striations are found on the under surface.

b) The second subdivision, namely, the inclusion of gravels by a rotary movement of the overlying rocks, is open to the same objections. It also necessarily involves the assumption of the glacial origin of the fold.

c) The opening of an irregular bedding plane by a slight movement, either rotary or lateral, which destroyed the registry of the irregularities is a possibility. The seam is, however, very regular; moreover, the glacial or post-glacial origin of the joints must be presupposed under this hypothesis.

The third view, the raising of the overlying beds by glacial action thus opening a seam, as one opens the leaves of a book, offers the fewest difficulties. However, it seems impossible that such a process could avoid moving and breaking the overlying rocks. A further difficulty is the comparatively regular thickness of fine gravel. If the frozen upper layers were simply buckled upward

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by glacial pressure, as one would buckle a sheet of paper by pushing slightly on one side, the explanation is perfectly adequate. It is not even necessary to assume a glacial origin for the fold, for

FIG. 5.—Gravel seam near entrance to quarry

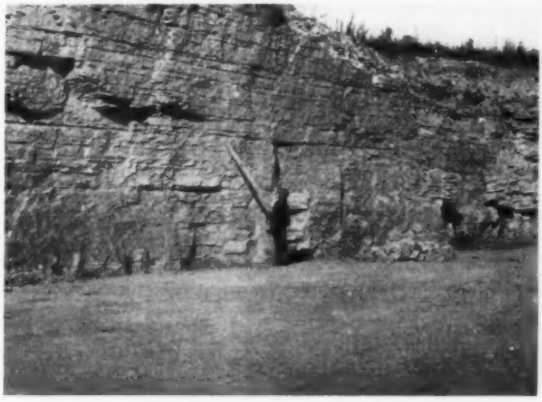

FIG. 6.—Gravel seam in west face of quarry, showing joints

pressure with the beds in their present position would account for the phenomenon. The filling can be ascribed either to glacial or to post-glacial waters, under this view.

Turning to the fourth hypothesis, it is significant that the gravel seam shows most weathering of all the bedding planes in the quarry, thus indicating that it has been a trunk channel for ground water. It is difficult, however, to understand, first, why the waters have followed only this particular plane; second, how they carried such comparatively large stones considering the size of the opening, and third, how they could produce so widespread and comparatively regular a sheet of gravel without at all affecting

FIG. 7.—Glacial gravel pocket in St. Peter sandstone. (Photograph by W. O. Hotchkiss.)

the large joints which pass through it. Being 10 feet below the surface, the seam is beyond the reach of frost under present climatic conditions unless air circulated through it, so that we cannot appeal with certainty to enlargement by freezing. It is possible that weathering of an originally soft layer has been the cause of lateral enlargement of the bedding plane parting so as to permit a widespread deposit of sand and gravel. In the case of the gashes and joints in the sandstone the effects of erosion by the gravel-carrying waters is clear, while the source of the filling might readily be the gravel deposit which overlies a portion of the exposure. The

position of the gravel seam in the quarry is not such, however, as to lend much support to this.

The writer has concluded that the balance of probabilities favors the view that the gravel seam is due primarily to glacial pressure, although solution has undoubtedly had a part in enlarging the parting. The gravel and sand may well have been in part deposited since the Glacial Period.

STRAND MARKINGS IN THE PENNSYLVANIAN SANDSTONES OF OSAGE COUNTY, OKLAHOMA[1]

SIDNEY POWERS
Tulsa, Okla.

INTRODUCTION
CONDITIONS OF SEDIMENTATION
DESCRIPTION OF MARKINGS
HYPOTHESES OF ORIGIN
CONCLUSIONS

INTRODUCTION

While mapping geologic structure in Osage County, Oklahoma, the attention of the writer was called to certain grooves on bedding planes which resemble glacial striae and slickensides, although clearly of strand origin. They are but one of the many kinds of markings formed along shores or in shallow water. From parallel groovings over broad areas there are all gradations to irregular markings which are clearly casts of impressions in the mud. The markings appear both on upper and lower surfaces of sandstone beds, but they are more common on lower surfaces.

Similar markings in sandy beds of the Portage group of the Upper Devonian of Naples, New York, have been described in detail recently by Dr. John M. Clarke[2] and many years ago by Professor James Hall.[3] They have also been found in the Strawn formation of Pennsylvanian (Pottsville) age, both south of Strawn, Texas, and east of San Saba, in San Saba County, Texas.[4] Grooves of similar nature are known in the Beekmantown of Valcour Island, Lake Champlain.[5] No doubt they are much more common than these few localities indicate.

[1] Published by permission of the director, United States Geological Survey.

[2] "Strand and Undertow Markings of Upper Devonian Time as Indications of the Prevailing Climate," *New York State Mus., Bull. 196* (1918), pp. 199–210.

[3] *Geology of the Fourth District of New York* (1843), pp. 234–37.

[4] The latter locality is known to Dr. J. A. Udden, of Austin, Texas.

[5] Personal communication from Dr. Rudolf Ruedemann, of Albany, New York.

The writer is indebted for information and suggestions regarding these markings to his former associates on the United States Geological Survey, Clarence S. Ross and Kenneth C. Heald. The best localities were found by R. H. Wood and D. D. Conduit of the Survey.

CONDITIONS OF SEDIMENTATION

During the middle and upper Pennsylvanian, when shales, sandstones, and limestones of the Osage were being deposited, a shallow sea with a continually oscillating shore line covered eastern Oklahoma and Kansas, and west-central Texas. The axis of the basin extended in a northeast-southwest direction with the southeastern shore line not far east of the eastern Osage and near the present outcrop of the Strawn formation in Texas.[1] The territory in Oklahoma in which the markings are found lies in the eastern Osage between Pawhuska, Hominy, Skiatook, and Tulsa. In this region limestones are thin and few, but highly fossiliferous. The sandstones commonly show ripple, current, and other strand markings; occasionally they are fossiliferous.[2] Stratigraphically the grooves are known in various horizons between the Hogshooter limestone and the Elgin sandstone, 1,000 feet apart. The Strawn formation in Texas is older than any of the Osage sediments.

DESCRIPTION OF MARKINGS

Nothing unusual has been noted in the current, ripple, and rill marks in the Osage sediments except that the current and rill markings appear in various stages of obscurity and some of the markings defy classification. They appear both on the upper and lower surfaces of sandstone layers. The nature of the parallel groovings may be judged by the photographs.

Localities in the Osage where markings may be seen are numerous. A few are given in the following list: (1) S.E. cor., N.E. ¼, Sec. 8, T. 20 N., R. 12 E., near F. A. Gillespie No. 1 (by R. H. Wood and the writer); (2) on

[1] Mr. A. W. McCoy, of Bartlesville, Oklahoma, has prepared extensive manuscript paleogeographic maps of these seas and has kindly given the writer the foregoing information and the correlation of the beds.

[2] "Structure and Oil and Gas Resources of the Osage Reservation, Oklahoma," *U.S. Geol. Survey, Bull. 686* (1919).

a bald hill in W.½, Sec. 7, same township (by C. S. Ross); (3) N.W. cor., Sec. 6, same township, a V-shaped groove (by C. S. Ross); (4) Sec. 14, T. 24 N., R. 8 E. (by K. C. Heald); (5) N.W. ¼, S.W. ¼, Sec. 10, T. 25 N., R. 9 E. (by K. C. Heald, D. D. Conduit, and the writer); (6) Sec. 11, T. 21 N., R. 11 E. (by C. S. Ross, P. V. Roundy, and the writer); (7) in the stone wall surrounding the house of Tom Gilchrist and in the foundation of the house of A. P. Kennedy a mile northwest of the Tulsa Country Club, and in a stone house on Duluth Street south of the Country Club (by C. S. Ross and the writer).

The Osage grooves occur on hard, massive sandstones ½ foot to 2 feet in thickness and are seen over broad surfaces or on slabs 1 foot to 5 feet in length. The only pronounced markings, like those illustrated, occur on under surfaces of blocks probably underlain by sandy shale. The grooved block at locality (6) above appears to be in place with rather poor ridges on the upper surface. Near Pawhuska (locality [5]) the markings are faint lines and fainter ridges not over ¼ inch in height seen in places on the upper surface of a bed exposed on the top of an unused quarry. They are subparallel and may be found for a distance of 70 feet measured across the ridges, but nowhere for a distance of more than 6 feet along the ridges.

The markings are rounded and smooth. They sometimes have vertical or even undercut sides and characteristically are covered with minute parallel lines on the sides of the larger ridges. Clearly defined V-shaped grooves are infrequent (Fig. 6). The width varies from that of a pencil line to 2 inches; it is uniform until the marking disappears. Neither depth nor height is, as a rule, more than ½ inch, but either may vary quite abruptly or be undulating in any single marking. Single straight markings with a relief of 2 to 3 inches are found alone and also associated with the other strand markings. Their origin apparently is similar to that of the parallel ones. Professor Hall (*op. cit.*) described one cast 6 inches in diameter. The relief of the surface shown in Figure 1, 5½ feet in length across the markings, is not more than 1 inch. No uniformity of spacing between the larger grooves in the cast has been observed. In some cases there are no coarse markings. Small ridges and large grooves in the cast seem to be the rule in one locality, but with the irregular and complicated markings, such as

FIG. 1.—Block of sandstone 5½ feet in height showing parallel strand markings on a bedding plane. This is the lower surface of the bed and the markings are casts of the original. As shown by the ruler in one of the upper grooves, the coarser markings are grooves in this cast. The relief of the surface is less than 1 inch. Locality, S.E. cor., N.E. ¼, Sec. 8, T. 20 N., R. 12 E., Osage County, Oklahoma. Photo by Lucian Walker, of Tulsa, Oklahoma.

FIG. 2.—Another block of sandstone at the same locality as Figure 1, showing a curve in parallel markings, and also showing irregular markings which are depressions in the cast. Nothing but flexible objects such as fronds of algae could have produced a curve in some of the markings and not in others when dragged along the strand. The irregular markings near the top may be casts of stranded algae. Photo by R. H. Wood, United States Geological Survey.

Figure 5, the reverse is the case, and there are no depressions in the cast.

Parallelism is the striking characteristic of the markings: they are as straight and as parallel as if ruled with a straight-edge. Yet frequently the grooves end abruptly, but smoothly as seen in Figure 3, or the ridges and grooves in the cast may disappear one by one in a deep, curved, and narrow groove whose beginning is

FIG. 3.—Irregular markings in another block of sandstone at the same locality as Figures 1 and 2. Suspended fronds of seaweed waving back and forth could produce these sinuous, intersecting fine grooves and ridges.

one of the grooves, but whose depth (a sharp ridge in the original) is fully $\frac{1}{2}$ inch. It is a sort of festoon, an arrangement very common in pahoehoe lava where the rumples in the lava are suddenly swept beneath the surface in a smooth curve. Sometimes some of the markings end in a rude curve or are curved along their length, the original direction being resumed beyond the curve (Fig. 2), while the other markings on the same slab are perfectly straight. Associated with some of the grooves are irregular small depressions and less abundant elevations in the cast (Fig. 2,

upper corner, Fig. 4). Cross-markings are infrequent in the well-striated surfaces, but common in the more irregular markings described below (Figs. 3, 6, 7). Professor Hall, however, figured one well-striated slab with three sets of parallel furrows.[1]

FIG. 4.—A slab of sandstone and a plaster cast of the same showing the original strand surface in the cast. The markings were depressions in the strands. Some of them represent very small dents made by objects swept along, but two of them strongly suggest nodal impressions of plants which, it is believed, lay on the strand. Locality, Naples, New York; Portage group of the Upper Devonian. Specimen in the New York State Museum.

Fossils are occasionally found in the grooves, but small rod-like impressions and gouges in the strand, as seen in Figure 4, are more common. Drifted shells fill grooves in the Beekmantown of Valcour Island, Lake Champlain, according to Dr. Ruedemann. Hall figures a slab showing on the original strand surface, two

[1] Reproduced by Clarke, *op. cit.*, p. 202.

broad ridges separating a broad groove, the latter being filled with drifted shells which washed in after the surface was marked.

Common strand markings have not been noted on the same slab with the most clearly defined grooves and ridges, but well-developed asymmetrical ripple marks, rill markings of various kinds, small irregular markings such as might represent worm

FIG. 5.—Casts of irregular markings, depressions in the strand, which appear to represent fronds of algae which lay on the beach. Near the right lower corner there is a piece of sandstone in the groove which in the original specimen looks suspiciously like the reverse side of a flattened stem of frond. Locality as in Figure 4.

tracks or burrows or algae have been found on sandstones either of the same bed or of beds higher or lower in the series. There are also smooth lumps which might have been lumps of sandy mud, faint single grooves or ridges, and faint symmetrical ripple marks with or without minute, superimposed, tubular lumps and worm tracks, the whole glazed with a thin film of iron oxide as are most of the markings.

Irregular markings, mostly grooves in the casts, are characteristic of many slabs of sandstone associated with the parallel markings. In Figure 3 they have the appearance of being made by objects swept back and forth on the strand while suspended from one or more common centers. Still more irregular markings (Fig. 5), all depressions on the strand, are composed of curved and crossed tubular casts, in cases more than an inch in diameter, and appear to represent casts of algae (or of something similar) which settled in the mud. From this state of irregularity it is but a step to nondescript markings the origin of which is probably inorganic.

Owing to the occurrence of most of the grooves on upturned blocks and to the fact that the beds underlying the casts have not been seen, it is not always possible to determine the original direction of the markings. In Sec. 11, T. 21 N., R. 11 E. it is N. 80° W.; in Sec. 10. T. 25 N., R. 9 E., N. 44°–52° W., which directions are down the depositional dip.

Plant remains have been found in one of the sandstone blocks associated with the grooved blocks in Sec. 8, T. 20 N., R. 12 E. and they occur in sandstone stratigraphically within a few feet of the grooves in Sec. 11, T. 21 N., R. 11 E. Casts of tree trunks have been found in abundance in the section 100 feet from the grooves in the former locality and the very fossiliferous Avant limestone is 80 feet from the grooves in the latter locality.

HYPOTHESES OF ORIGIN

Various hypotheses may be presented for the origin of the grooves: (1) impressions of plant remains, (2) dragging of parts of trees or roots, of algae or of pebbles over the strand, (3) action of ground ice molding unconsolidated sandy clays, (4) differential slipping of the beds before consolidation, (5) tidal action. These hypotheses will be examined in order.

1. *Impressions of plant remains.*—Trunks of trees or branches of algae impressed on the sandy mud could not have made the parallel striations such as are shown in Figure 1. They may well, however, account for some of the single markings, such as Figure 6. Definite worm trails are found on sandstones associated with the

grooved sandstones and casts of branching and interlacing stems generally admitted to represent algae are very common in the Osage rocks. Some of the slabs in the New York State Museum (Figs. 4, 5) show markings which, in the opinion of the writer, were formed as impressions of either algae, or of wood and nodes of plants. In some cases they show faint striations like the plant impressions of the same size on the Joggins section, Nova Scotia, or in the North Sydney section, Cape Breton Island (plates 18 and 22 of Clarke). In other cases the rounded elevations (filling

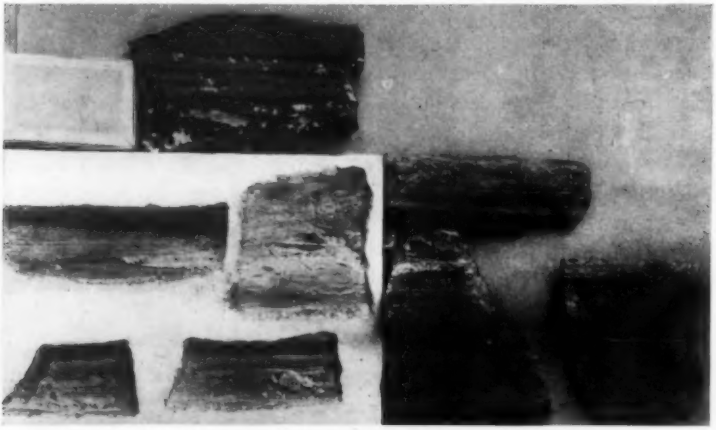

FIG. 6.—Blocks of sandstone in which are casts of V-shaped grooves and which are themselves grooved with sinuous lines. The plaster cast at the left shows the original. A branch or root dragged over fine-grained argillaceous sand could produce such grooves. Locality, Strawn, Texas. The block of sandstone at the top shows somewhat comparable markings produced by weathering of cross-bedding. Locality, basal Eocene, southeast of Uvalde, Texas.

of depressions in the original strand surface) may be partly broken from the rock (Fig. 5), showing that they had an upper as well as a lower surface and may represent casts of kelplike material. In the Tesnus formation of Pennsylvanian (Pottsville) age, 9 miles south of Marathon, Texas, and 225 feet below the top of the formation, there is a heavy sandstone bed showing mud flow and ripple marks and plant casts, but no groovings.

Short, rodlike markings of obscure origin, so-called *Fucoides graphica*, recently have been ascribed to ice crystals by Dr. Clarke at the suggestion of Professor Woodworth.[1] Dr. Udden has enlarged on the suggestion by redescribing similar markings in the Cretaceous of Texas and of the Black Hills as fossil ice crystals.[2] The markings resemble the shorter ones on Figure 4. They are either straight or curved; they are 1 inch to 2 inches in length and $\frac{3}{16}$ to $\frac{1}{4}$ inch in diameter. The same markings are common in the Osage, and in the continuation of the same sandstones near Henryetta, Oklahoma. Faint markings of the same shape occur in the same horizon as some of the grooves. Measured ice crystals have not exactly the same shape as most of the supposed fossil crystals, but the branching and radiating forms are similar. The specimens in the New York State Museum show that the supposed crystals represent casts of crystals or of objects partly buried in the mud, because the ridges in the cast where they join or cross are distinctly superimposed, and in one case the newer object has bent down the older one. Ice crystals could scarcely bend one another, nor could they be depressed by any objects moving over or resting on them. Worm tubes, as

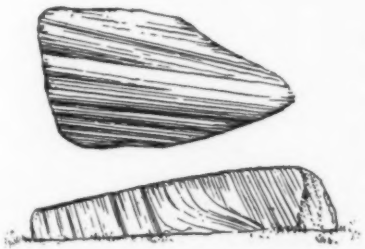

FIG. 7.—Casts of diverging grooves on the lower surfaces of sandstone blocks. The upper figure shows a slab 4 feet long in stone wall near Tulsa Country Club, Tulsa, Oklahoma; the lower figure shows a slab 5 feet long at the same locality as Figure 1.

[1] J. M. Clarke, *op. cit.*, p. 205; J. B. Woodworth, *et al.*, "The Glacial Brick Clays of Rhode Island and Southeastern Massachusetts," *17th Ann. Rept., U.S. Geol. Survey* (1896), Part 1, p. 992; T. M'K. Hughes, "On Some Tracks of Terrestrial and Fresh Water Animals," *Quar. Jour. Geol. Soc.*, London, Vol. XL, No. 157 (1884), p. 184; J. E. Talmage, "Notes Concerning Certain Linear Marks in a Sedimentary Rock" (Abstract), *Quar. Jour. Geol. Soc.*, London, Vol. LII (1896), p. 461; *Univ. Utah Quarterly* (December, 1895).

[2] J. A. Udden, "Fossil Ice Crystals," *Univ. of Texas Bull. (1821)*, (1918); *Sci. Amer.*, Vol. LXXII (1895), p. 102; "A Sketch of the Geology of the Chisos Country, Brewster County, Texas," *Univ. of Texas, Bull. 93 (Science Series No. 11)* (1907), p. 32; D. D. Christner and O. C. Wheeler, "The Geology of Terrell County, Texas," *Univ. of Texas Bull.* (1918), p. 15.

beautifully exhibited in slabs forming pillars at the south entrance to the Tulsa Country Club (Tulsa, Oklahoma) characteristically are superimposed, and have the same diameter as the supposed crystal tubes. It is barely possible that climatic conditions in the several geologic periods in which these markings were formed were such that ground ice and ice crystals could form.

2. *Dragging of parts of trees or roots of algae or of pebbles over the strand.*—Groovings in sandy clay may be produced by shoving or dragging objects over the surface either above or below water. The alga, *Ulva enteromorpha*, has been observed dragging pebbles over the strand making depressions.[1] Ulva grows in tufts 6 to 8 inches high attached to one side of pebbles as large as $\frac{3}{4}$ inch in diameter. The fronds stand upright from the anchoring pebble, and wave back and forth dragging the pebble, but not lifting it. Either single or double grooves are produced, and the grooves in the illustrations cannot be distinguished from many of the single Osage grooves. One can readily imagine how this operation could produce many of the irregular Osage markings, especially those which cross (Fig. 3), but pebbles are very rare in the Osage sediments.[2] To produce parallel groovings bunches of large algae could be washed along by the tide, and where the algae came to rest irregular depressions would be produced in the sandy shale as stated above. Curves in the grooves, especially in some and not in others, could readily be produced by obstructions in the path of the algae (Fig. 2, upper corner) or by swirls in the tidal action, or by undertow.

Fragments of fossil wood indicate the presence of trees at the same horizon as the parallel markings. Were a log washed over the strand it would normally rotate; were a stump dragged along some of the roots would make deep, sharp-pointed grooves and ridges such as are occasionally found alone (Fig. 6). A log could not make the curved and diverging markings, but light pieces of wood could produce superimposed series of striations. Single grooves with finely striated sides unassociated with other

[1] A. P. Brown, "The Formation of Ripple Marks, Tracks, and Trails," *Proc. Acad. Nat. Sci.*, Philadelphia, Vol. LXIII (1911), pp. 536–47.

[2] C. S. Ross reports a conglomeratic limestone in the south part of T. 22 N., R. 7 E., that contains gravels and small pebbles of white vein quartz, igneous, and metamorphic rocks which were possibly carried by floating ice.

strand markings have the appearance of being made by roots or other portions of trees.

3. *Action of ground ice molding unconsolidated sandy clays.*—Floating land ice has been shown by Lyell to be capable of furrowing consolidated sandstone.[1] Dr. Clarke and Professor Woodworth concur in the opinion that the markings in the Upper Devonian of New York are of similar origin. The occurrence described by Lyell was at Cape Blomidon, on the Bay of Fundy, where heavily "packed" ice often 15 feet thick with fragments of amygdaloidal basalt frozen in the base, is pushed over ledges of Triassic sandstone with the rise of the tide.

Climatic conditions such that land and ground ice could be formed at various times during the deposition of 1,000 feet or more of sediments in the middle and upper Pennsylvanian are within the range of possibility and the faunas and floras would not necessarily prove or disprove such an assumption.[2] But if floating ice were present it should have gouged out the muds in some places and produced considerable lumps in others. Contrast the absence of such disturbances with Dr. Kindle's description of the action of "ice-shoved bowlder or ice cake" in the Mackenzie River:

> The plowing and gouging action of ice is nearly everywhere in evidence along the Mackenzie. At the head of the river, in the eastern shallow channel, one can see through the clear water numerous deep grooves made by ice cakes or bowlders pushed by ice in the bowlder clay of the bottom. In the gravel or slits of low islands the broad grooves made by ice-shoved bowlders or ice blocks can often be traced for a considerable distance. In some localities the plowing and scooping action of the ice carries quantities of mud from the bottom to the banks of the river.[3]

A comparatively smooth surface on the bottom of the ice would produce the required parallel markings and might produce cross-markings, but not the irregular markings unless small cakes of

[1] *Travels in North America*, Vol. II (1845), p. 144.

[2] "It seems possible to state that there is evidence for presuming that the Permian glacial period was preceded in the Carboniferous by a degree of cold permitting floating ice in continental bodies of water and also in the sea in middle latitudes."—J. B. Woodworth, "Boulder Beds of the Caney Shales at Talahina, Oklahoma," *Bull. Geol. Soc. Amer.*, Vol. XXIII (1912), pp. 457–62; quotation p. 462.

[3] "Notes on Sedimentation in the Mackenzie River Basin," *Jour. Geol.*, Vol. XXVI (1918), pp. 341–60; quotation p. 353.

ice floated or were dragged around. Some of the irregularities (largely sharp ridges and elevations in the original) might have been formed by the melting of ice around mud-filled cracks. There was no regional Pennsylvanian glaciation in the Osage, for tillites have not been found. Bowlders of large size which have been interpreted as indicating the presence of floating ice during the early Pennsylvanian (Pottsville) in the vicinity of the Arbuckle and Ouachita mountains has caused considerable discussion.[1] Recently Professor Samuel Weidman has found striated pebbles in the Franks conglomerate of the Arbuckle Mountains together with the striated floor of older rocks on which the conglomerate rests.[2] This conglomerate is much older than the sediments of the Osage. Another reported locality of tillite near Shafter, Presidio County, Texas, has been examined by the writer and is believed by him not to be tillite.[3]

Opposed to the theory of floating ice is the fact that nowhere are any of the striated sandstone beds gouged or beveled obliquely to the bedding planes; nor are the latter in any way disturbed. The varied and complex strand markings, which are much more abundant than the grooves on the various blocks of sandstone at the same locality, have never been rubbed by ice.

4. *Differential slipping of beds before consolidation.*—Slipping in unconsolidated beds, especially in muds and silts, is a well-known phenomenon recently emphasized in the mud lumps of the Mississippi delta[4] and in experiments by Dr. Kindle.[5] The latter

[1] J. A. Taff, "Ice-borne Boulder Deposits in Mid-Carboniferous Marine Shales," *Bull. Geol. Soc. Amer.*, Vol. XX (1909), pp. 701–2; *Science* (New Series, Vol. XXI (1905), p. 225; E. O. Ulrich, "Revision of the Paleozoic Systems," *Bull. Geol. Soc. Amer.*, Vol. XXII (1911), p. 352, footnote; J. B. Woodworth, *op. cit.*

[2] "The Probability of Pennsylvanian Glaciation of the Arbuckle Mountain Region," *Bull. Geol. Soc. Amer.*, Vol. XXXII (1921).

[3] J. A. Udden, "The Geology of the Shafter Silver Mine District, Presidio County, Texas," *Univ. of Texas Mineral Survey, Bull. 8* (1904), pp. 14, 59. The only conglomerates found by the writer are at the base of the Cieneguita series as determined by the intrusive contact with syenite porphyry. They are very fine conglomerates and sandstones composed of rounded quartz pebbles and grains which look like fragments of vein quartz rounded by long water erosion.

[4] E. W. Shaw, "The Mud Lumps at the Mouths of the Mississippi," *U.S. Geol. Survey, Prof. Paper 85b* (1914), pp. 11–27.

[5] E. M. Kindle, "Deformation of Unconsolidated Beds in Nova Scotia and Southern Ontario," *Bull. Geol. Soc. Amer.*, Vol. XXVIII (1917), pp. 323–34.

has shown that when soft beds are overlain by unequally disturbed heavier and firmer beds there is a marked deformation of the former caused by differential weighing of the firmer upper beds. In the Osage the overlying heavy sandstones are equally distributed over large areas, but were the strands inclined, slipping could conceivably take place in sediments of the right composition producing modified slickensides on the bedding planes.[1] Again, were there readjustments within the subsiding geosynclinal basin during deposition, such as faulting, which Mr. A. W. McCoy tells the writer took place in the Osage basin, slipping would be expected along bedding planes, just as slipping is known to have been caused by earthquakes.

Difficulties not overcome by a slipping hypothesis, even assuming that sandy clays and sandstones would slide, are the explanations of systems of cross-markings, and the absence of buckling of the strata or of intraformational conglomerate. Slickensiding after consolidation is not a possibility because the markings are clearly molded, not gouged.

5. *Tidal action.*—Current and tidal action produce a variety of markings on the strand, a number of which have been figured by Dr. Clarke and which can be reproduced in the Osage sandstone and in the Tesnus formation sandstone of the Marathon region, Texas; especially the "mud flows" which are interpreted as plunge and undertow markings of retreating waves on the beach. The larger ones, which are 2 to 5 inches in width and 1 inch in depth may have been formed, as suggested to the writer by Mr. C. A. Hartnagel, of the New York State Museum, in tiny puddles of water on a gently sloping beach swirled by sudden gusts of wind. Professor Hall's theory of the origin of the parallel markings is by current action:

> The only assignable cause for these ridges is the action of a current flowing over the surface of the strata, sometimes transporting sand and at other times coarser material which furrowed the surface upon which the subsequent deposits were made.[2]

[1] Dr. J. A. Udden has kindly called the attention of the writer to photographs of sandstone slabs showing minute faults and wavy subparallel folds, the origin of which he believes to have been creep of settling muds before consolidation, but these folds do not resemble the strand markings (*Univ. of Texas, Bull. 246* (1912, Pl. 25).

[2] *Op. cit.*, pp. 234–35.

Cross-bedded sandstones may show very similar grooves and ridges when relief is accentuated by weathering (Fig. 6), but the two kinds of markings are entirely distinct in origin.

CONCLUSIONS

Parallel groovings on bedding planes such as described above have been shown to be markings on the original strand either in sandy clay or in a fine-grained sandstone. Preservation of either the original surface, as in the case of the sandstones, or of a cast of the surface, as in the case of the sandy clays, has failed to reveal both original and cast of any one set of markings except in the form of small fragments.

Inspection of the various theories which may be advanced to account for the formation of such strand markings shows that they have been formed by the dragging of plants, probably stems and fronds of algae, over sand and mud in shallow water, probably by tidal or undertow currents. Ground ice and shore ice are shown to be incapable of having made these markings.

Reasons for the conclusions above may be briefly summarized: (1) general distribution through formations of similar origin, but of different ages in various regions; (2) perfect parallelism over broad surfaces with notable undulations and sinuosities confined to certain of the markings; (3) curved, overlapping, and cross-striations; (4) absence of any disturbance within the strata; (5) intimate association with beach and shallow water markings as current, ripple, rill marks, worm borings, and algal impressions; (6) occasional association with heaps of shells found in the grooves and stratigraphic proximity of plant remains; (7) negative evidence of the presence of ice in any form or of glacial deposits in the containing formations; (8) complete gradation from straightness to curvature to cross-markings and more irregular markings showing nodal and stemlike impressions; and (9) the outstanding delicacy of the whole, showing that gouging was subordinate to molding by objects of light weight.

SUMMARIES OF PRE-CAMBRIAN LITERATURE OF NORTH AMERICA

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V. THE EASTERN PART OF THE UNITED STATES

During the period covered by these summaries, the following United States Survey quadrangle areas containing pre-Cambrian rocks have been mapped: the Raritan quadrangle of New Jersey, the Tolchester quadrangle of Maryland, and the Ellijay quadrangle of Georgia. The New York State Museum has published several papers on Adirondack areas. The Federal Survey has published Emerson's bulletin on the "Geology of Massachusetts and Rhode Island."

One of the most notable advances is the determination of the pre-Cambrian age of the Wissahickon mica gneiss of southeastern Pennsylvania by Bliss and Jonas. In Vermont, the unconformable contact between Cambrian and pre-Cambrian has been more clearly defined by Dale and by Keith. The Ocoee group in the south is now placed by the Federal Survey with the Cambrian. This is still largely a matter of arbitrary decision. The apparently conformable gradation of Ocoee into Cambrian is interpreted by Keith and associates as evidence of the Cambrian age of the Ocoee. The lack of fossils in the Ocoee has been emphasized by Van Hise and Leith as a pre-Cambrian trait.

The Raritan quadrangle[1] lies in both the Appalachian and Coastal plain provinces of northern New Jersey. For purposes of mapping, the pre-Cambrian rocks of the quadrangle are classified as the Franklin limestone, Pochuck gneiss, and graphite schists, all of sedimentary origin. The Byram gneiss is a gray granitoid igneous rock composed of microcline, microperthite, quartz, and

[1] W. S. Bayley, R. D. Salisbury, and H. B. Kummel, "Description of the Rariton Quadrangle, New Jersey," *U.S. Geol. Surv., Geol. Atlas*, U.S. Raritan Folio (No. 191) (1914). 32 pp., 21 figs., 5 maps, section sheet.

hornblende with a little pyroxene and biotite. The constituents of the Losee gneiss are quartz, oligoclase, pyroxene, and some hornblende and biotite. The Pochuck gneisses are mostly of unknown origin, but in part are igneous. They are dark-colored rocks composed of pyroxene, hornblende, oligoclase, and magnetite. The stratigraphic relations of the pre-Cambrian rocks have not been worked out. Their classification is lithological. They are believed to be related to the Grenville series of the Adirondacks and southeastern Canada.

Bayley[1] reports that the pre-Cambrian rocks of the highlands of New Jersey include a series of limestone, quartzites, conglomerates, slates, and micaceous schists whose stratigraphic succession is uncertain. They are surrounded by older and in part igneous gneisses.

Bliss and Jonas[2] conclude that the Wissachickon mica gneiss of the Doe Run and Avondale region of southeastern Pennsylvania is of pre-Cambrian age and is separated by a thrust fault from Ordovician limestone.

Cushing and Ruedemann[3] describe the Saratoga Springs area which lies in the eastern central portion of New York state. It includes portions of the Adirondack highlands, New England plateau and the Champlain downwarp. The pre-Cambrian rocks include Grenville sediments intruded by Laurentian granite. Later intrusions of anorthosite, syenite, granite, and gabbro followed in the order named. The Grenville sediments consist chiefly of a variety of schists probably representing metamorphosed muds. Associated with them is a belt of quartzite with some limestone lenses. The schistosity and bedding of the sediments are inferred to be parallel. The schistosity strikes east and west and dips southward at a low angle rarely reaching 40°.

[1] W. S. Bayley, "The Pre-Cambrian Sedimentary Rocks in the Highlands of New Jersey," *Congrès Geologique International*. (XII Session Canada, 1914, pp. 325-34.)

[2] Eleanora F. Bliss and Anna I. Jonas, "Relation of the Wissahickon Mica Gneiss to the Shenandoah Limestone and Octoraro Schist of the Doe Run and Avondale Region, Chester County, Pennsylvania," *U.S. Geol. Surv., Prof. Paper 98* (1916), pp. 9–34, 3 pls., 3 figs.

[3] H. P. Cushing and H. Ruedemann, "Geology of Saratoga Springs and Vicinity," *New York State Museum, Bull. No. 169*, 177 pp., 17 figs., 3 maps.

Dale[1] traced the boundary of the pre-Cambrian and the Cambrian rocks of Vermont for a distance of 60 miles and finds them to be structurally discordant and unconformable. The pre-Cambrian rocks include various granite gneisses, aplite gneiss, metamorphic arkoses, quartzite, conglomerate with pebbles of quartzite, albitic sericitic schists, and graphitic sericitic schist.

Eaton[2] states that the pre-Cambrian rocks of South Mountain, Pennsylvania, near 40° 20′ north latitude and meridian 76° 10′ west longitude, consist mainly of granite, diorite and gabbro gneisses cut by granite pegmatites. These gneisses probably correspond in age and composition to the Losee, Byram, and Pochuck gneisses of eastern Pennsylvania and New Jersey.

Emerson[3] recognizes two belts of pre-Cambrian rocks in Massachusetts, a western belt forming the backbone of the Green Mountains, the eastern belt extending from Rhode Island through Worcester and Essex counties, Massachusetts. The oldest rock in the western belt is the Hinsdale gneiss, a coarse granitoid gneiss including beds of limestone, quartzite, micaceous graphitic schists. Coarse feldspathic rocks locally replace the limestones. Hornblendic and fibrolitic rocks are also included in the Hinsdale gneiss. In the upper portion of the Hinsdale gneiss is the Cole Brook limestone, a coarse magnesian limestone, highly metamorphosed and about 600 feet thick. A more quartzose gneiss than the Hinsdale is called the Washington gneiss. The dominantly igneous pre-Cambrian rocks of western Massachusetts include the Stanford granite gneiss, titanite-diopside, diorite aplite, Lee quartz diorite, Becket granite gneiss, and dunite.

The oldest pre-Cambrian rocks in the eastern belt is the Northbridge granite gneiss. With apparent unconformity, it is overlain successively by the Westboro quartzite and the Marlboro formation, both doubtfully pre-Cambrian. The latter is a biotite schist.

[1] T. Nelson Dale, "The Algonkian-Cambrian Boundary East of the Green Mountain Axis in Vermont," *Am. Jour. Sci.*, 4th Ser., Vol. XLII (1916), pp. 120–24, 1 fig.

[2] H. N. Eaton, "The Geology of South Mountain at the Junction of Berks, Lebanon, and Lancaster Counties, Pennsylvania," *Jour. Geol.*, Vol. XX (May–June, 1912), pp. 331–43, 2 figs.

[3] B. K. Emerson, "Geology of Massachusetts and Rhode Island," *U.S. Geol. Surv., Bull. 597* (1917), 289 pp., 10 pls., 2 figs.

Fenner[1] advocates the theory of the origin of certain gneisses by injection.

Katz[2] tentatively assigns certain quartzites, slates, and schists of southwestern Maine to the Algonkian because of their lithologic resemblance and area and structural relationship to the Westboro quartzite and Marlboro formation of eastern Massachusetts.

Keith[3] has traced an unconformity at the base of the Cambrian along the west border of the Green Mountains, and concludes that certain older sediments beneath the unconformity are properly classed as Algonkian.

La Farge and Phalen[4] follow Keith in placing the Ocoee group of the southern Appalachians in the Cambrian. In the Ellijay quadrangle of northern Georgia they recognized several groups of pre-Cambrian rocks, all of which they classify as Archean.

The most abundant types comprise an older complex of acid schists and gneisses whose origin is doubtful, and a younger group of areally less extensive basic gneisses and schists, mostly dioritic gneiss which is intrusive into the older complex. The first is known as the Carolina gneiss, the latter as the Roan gneiss. Intimately associated with the Roan gneess, are small masses of pyroxenite and dunite which are probably intruded into the Roan gneiss. Both the Roan and the Carolina gneiss are intruded by small masses of granite believed to be Archean in age.

Martin[5] recognizes a Grenville series and post-Grenville intrusives in the Canton quadrangle of northern New York. The Grenville includes limestones, garnet, and siliceous gneisses, quartzites and quartz schist and amphibolite. The post-Grenville

[1] C. N. Fenner, "Mode of Formation of Certain Gneisses in the Highlands of New Jersey" (Abstract), *Geol. Soc. Am. Bull.*, Vol. XXV, No. 1 (March 30, 1914), pp. 44–45.

[2] F. J. Katz, "Stratigraphy in Southwestern Maine and Southeastern New Hampshire," *U.S. Geol. Surv., Prof. Paper 108* (1918), pp. 165–77.

[3] A. Keith, "A Pre-Cambrian Unconformity in Vermont," *Geol. Soc. Am. Bull.*, Vol. XXV, No. 1 (1914), pp. 39–40.

[4] L. La Farge and W. C. Phalen, "Georgia, North Carolina, Tennessee," *Ellijay Folio, No. 187* (1913), 17 pp., 4 maps.

[5] James C. Martin, "The Pre-Cambrian Rocks of the Canton Quadrangle," *New York State Mus., Bull. No. 185* (1916), 112 pp., 20 pls., 31 figs., maps.

intrusives listed are gabbro-amphibolite, granite gneiss, and pegmatite dikes.

Miller[1] gives the following classification of the pre-Cambrian rocks in the region of Bethlehem, Pennsylvania:

Algonkian	Franklin limestone
	Vera Cruz graphitic schist
Undifferentiated pre-Cambrian	Acid and basic igneous and sedimentary gneisses cut by dikes of basalt and pegmatite

Miller[2] and others describe the pre-Cambrian rocks of the Tolchester quadrangle east of Baltimore. The pre-Cambrian rocks include the acid Baltimore gneiss and the Wissahickon gneiss, both believed to be largely sedimentary. Their age relations are uncertain. These rocks are intruded by pre-Cambrian granite, gabbro, peridotite, and pyroxenite.

Miller[3] ascribes the foliation of the Grenville series of New York mainly to recrystallization caused by heat and pressure accompanying the upwelling of magmas, and only to a very minor degree to lateral compression. Low dips, parallelism between bedding and foliation, and general absence of small folds are the principal facts on which this view is based. The foliation of the granite syenite series, he thinks, is an original flow and crystallization structure. The same view is taken of the granulated anorthosite and gabbro phases.

Peck[4] states that the pre-Cambrian rocks of Chestnut and Marble hills in Northampton County, Pennsylvania, consist of a lower granitoid, gneissose series, overlain by a highly metamor-

[1] B. L. Miller, "The Mineral Pigments of Pennsylvania," *Pennsylvania Topog. and Geol. Surv., Rept. No. 4* (1911), 101 pp., 29 pls., 9 figs.

[2] B. L. Miller, E. B. Mathews, A. B. Bibbins, and H. P. Little, "Description of the Tolchester Quadrangle, Maryland," *U.S. Geol. Surv., Geol. Atlas*, Tolchester Folio (No. 204) (1917), 15 pp., 3 pls., maps and illus., 3 figs.

[3] W. J. Miller, "Origin of Foliation in the Pre-Cambrian Rocks of Northern New York," *Jour. Geol.*, Vol. XXIV (1916), pp. 587–619, 1 fig.

[4] F. B. Peck, "Preliminary Report on the Talc and Serpentine of Northampton County and the Portland Cement Materials of the Lehigh District, Pennsylvania," *Pennsylvania Topog. and Geol. Surv., Rept. No. 5* (1911), 65 pp., 17 pls. (incl. geol. map), 9 figs.

phosed series of rocks which vary widely in character, and include beds of limestone and dolomite.

Wherry[1] states that the pre-Cambrian rocks of Pennsylvania occur in three distinct belts: (1) the Catoctin belt extending southwest from Harrisburg into Maryland; (2) the Highland belt extending from a point about 40 miles east of Harrisburg and crossing the Delaware River at Easton; (3) the Piedmont Belt which stretches from Philadelphia to Trenton, New Jersey. About half of the pre-Cambrian rocks of the Highland belt are of sedimentary origin. The latter include crystalline limestones, quartz, mica schists, graphite-bearing quartzite, and amphibolitic gneiss, the latter being areally the most important. The principal facts on which belief in sedimentary origin of these rocks is based, include high silica and alumina content, high carbonate content, rounded zircons, the great longitudinal extent of the gneiss laminae, and the greater age of the laminae as compared with granitic intrusions of the region.

[1] E. T. Wherry, "Pre-Cambrian Sedimentary Rocks in the Highland of Eastern Pennsylvania," *Geol. Soc. Am. Bull.*, Vol. XXIX (1918), pp. 375–92.

[To be concluded]

Editorial Note

In Number 6, Volume XXVIII (1920), of the *Journal of Geology*, it was announced that, because of the extremely high cost of printing, it would be necessary to limit Volume XXIX (1921) to six numbers. This announcement was made with great regret. It is therefore with correspondingly great pleasure that the *Journal* now is able to make the announcement that, through the generosity of one of its associate editors, Dr. R. A. F. Penrose, Jr., formerly connected with the Department of Geology in the University of Chicago, the announced reduction in the volume will not be necessary. During the year 1921, the *Journal* will continue to be published semi-quarterly, as heretofore. The editors of the *Journal* and the University appreciate deeply the generous support of Dr. Penrose. Their feeling will be shared, we believe, by all who are interested in the science of geology.

Certain changes in the editorial policy of the *Journal* have been adopted. These are printed near the bottom of the inside page of the first cover of this number, and the attention of contributors is called to them.

Reviews

Fifteenth Biennial Report, Colorado Bureau of Mines, for 1917 and 1918. Denver: The State Printers, 1919.

The mining is considered by counties and by products. The history, recent development, production, and markets for the various ores are discussed. Non-metallic products are included; also a short note on oil shale possibilities.

In general the report shows that the mining industry of the state is declining. Since 1915 the production of gold in the Cripple Creek district, the chief gold center of the state since 1893, has decreased from $13,683,494 to $8,300,000 (estimated) in 1918. The production of silver in Lake County (the leading silver-producing county) has fallen from 4,154,913 ounces in 1907 to 2,353,530 ounces (estimated) in 1918, although 1914 was a relatively good year. The production of lead has decreased less than that of the precious metals, but the decrease in both copper and zinc has been considerable in recent years. Lake County produces more silver, lead, copper, and zinc than any other. In 1916 the state produced nearly $5,000,000 worth of tungsten, but the estimate for 1918 is less than half this figure, due to decreased demand and possibly to the irregularity of the veins.

Colorado leads the world in the production of molybdenum, the main deposit (said to be the largest known) being in the western part of Summit County. In 1918 the state had an estimated production of 94,000 pounds of uranium, the largest except in 1914. Two million pounds of vanadium (largest production to date) is the estimate for 1918.

The total mineral production of the state to 1917 is as follows:

Gold	$623,047,160	.....
Silver	466,463,217	593,796,442 fine ounces
Lead	173,909,020	3,962,140,896 pounds
Copper	35,755,138	237,422,282 pounds
Zinc	106,310,030	1,484,929,849 pounds
	$1,405,484,565	

D. J. F.

Coals and Structure of Magoffin County, Kentucky. By ILEY B. BROWNING and PHILIP G. RUSSELL. Frankfort: Kentucky Geological Survey, 4th Series, Vol. V, Pt. II, with geologic ection and maps, 1919. Pp. x+552.

This is a detailed report on the subject named in the title. The columnar section accompanying the report shows twenty-three beds of coal, not all workable, most of which are in the Pottsville Series. It is stated that only three horizons in the 1,200 foot section are sufficiently persistent and well defined to be serviceable as horizon markers. It is stated that all the strata exposed are of marine origin.

R. D. S.

Oil and Gas Resources of Kansas. By RAYMOND C. MOORE and WINTHROP P. HAYNES. Lawrence: State Geological Survey of Kansas, Bulletin 3. 391 pages, 40 plates.

The volume contains a historical sketch of the oil and gas industry of the state, and brief discussions of a general nature on (1) the origin of oil and gas, (2) their migration and accumulation, and (3) methods of production, refining, etc. These discussions are followed by a summary of the stratigraphy of Kansas (pp. 78–173), including the fullest account to date of the sub-surface crystalline rocks of the state. These rocks (granite) are said to constitute a buried ridge nearly 175 miles long and 10 to 25 miles wide, trending in a northeast-southwest direction (really north-northeast, south-southwest) from the Nebraska line near Bern, to northern Butler County. Its highest elevation is at the north, where its top is about 600 feet below the surface, and its maximum height above the surrounding crystalline rock floor probably is 2,500 feet or more. The age of the granite is conjectured to be pre-Cambrian, and to have been uplifted in the late Mississippian or early in the Pennsylvanian.

These preparatory chapters precede the main topic of the bulletin, the production of oil in Kansas (pp. 194–397). Most of the oil of the state is from the Pennsylvanian system, but the Permian, and perhaps the Mississippian, have yielded some. The production of oil in 1916, the last year for which data are given, was about 8,750,000 barrels, more than twice that of any preceding year. In 1916 more than 3,600 new wells were completed, about 10 per cent of them dry.

A small but clear geological map of the state accompanies the volume, also a map showing the distribution of oil and gas.

The volume bears no date on title-page, or elsewhere where a date is naturally looked for, though the date 1917 appears under the state printer's name. Its publication appears to have been delayed, as so many other volumes have been in recent years.

R. D. S.

Petroleum and Natural Gas in Indiana. By W. M. LOGAN, State Geologist. Fort Wayne: The Department of Conservation, Division of Geology, 1920. Pp. 279.

Like the preceding, this volume appropriately discusses the general fundamental questions concerning the origin and accumulation of oil and gas, and methods of finding it (pp. 10–48). A summary of the stratigraphy of the state (pp. 50–62) is followed by reports on the several counties. A map showing the oil and gas areas of the state accompanies the report.

R. D. S.

The Sand and Gravel Resources of Missouri. By C. L. DAKE. Rolla: Missouri Bureau of Geology and Mines. Vol. XV, 2d ser. (1918). Pp. xii+274, 17 plates.

A useful volume, dealing not only with the geological phases of the subject, but with the industrial phases as well. It is not restricted to surface sands and gravels, but includes available materials of these types in formations from the Cambrian up. Incidentally the volume presents a brief, up-to-date summary of the stratigraphic succession of the state, which is welcome and useful. The volume should be of value to those engaged in most sorts of construction work, both now and in the future, as well as to geologists.

R. D. S.

The Physical Features of Anne Arundel County. By HOMER P. LITTLE and OTHERS. Baltimore: Maryland Geological Survey, 1917. Pp. 232, pls. 9.

This county report covers the physiography, geology, mineral resources, soils, climate, magnetism, and forests. The county lies in the coastal plain, and formations older than the Cretaceous therefore are wanting. One of the striking features of the geology of the region is the large number of unconformities in the Coastal Plain series. There

are, for example, seven Cretaceous formations, each bounded above and below by an unconformity. Much the same may be said of the later formations. The Cretaceous strata of the region have a total thickness of 720 feet, the Eocene, 160 feet, the Miocene, 100 feet, the Pliocene (?), 40 feet, and the Pleistocene about 100 feet.

R. D. S.

Onaping Map-Area. By W. H. COLLINS. Ottawa: Canadian Geological Survey, Memoir 95, 1917. Pp. viii+157, pls. 11, figs. 8, map.

A very concise report on the geology of an area of approximately 3,500 square miles the center of which is 50 miles north of Sudbury. The area lies within the southern part of the pre-cambrian shield and its topography is that of a hummocky plateau 875 to 1,450 feet above the sea. The most important physiographic features antedate glaciation. The two intersecting series of parallel lake basins, in the southwest quarter of the area, probably follow faults.

The solid rocks, all pre-Cambrian, are separable by a great unconformity into a pre-Huronian group and a Huronian group. The pre-Huronian consists of a schist-complex and intrusive granite-gneisses. The schist-complex consists of volcanics and subordinately of water-deposited tuffs, iron-formation, and other sediments. The structure of this schist-complex, wherever determinable, is that of low anticlinoria and synclinoria. Dynamic metamorphism has converted the original volcanics and sediments into chlorite and sericite or paragonite schists. Near the granite-gneiss batholiths the effects of contact metamorphism are very marked. This schist-complex represents a period of extensive vulcanism and the formation of shallow-water or land deposits. The intrusive granite-gneiss series is dominantly granodiorites with which are associated a great variety of amphibolites, diorites, aplites, pegmatites, and other types. The diversity of types is explained by primary differences in the intruding magma, magmatic differentiation, and large-scale magmatic assimilation of older rocks. Crenulated interlocking contacts of larger mineral individuals with irregular shape and orientation are textural features very characteristic of these assimilated products. Good photomicrographs are shown to illustrate these features. In the future these criteria may prove of great assistance in determining this obscure type of metamorphic rocks.

The Huronian rocks constitute the Cobalt series, divisible into two parts. The lower part (Gowganda formation, 0–3,000 feet thick)

is composed of conglomerates, greywackes characterized by incomplete weathering and imperfect sorting, and a few beds of limestone. By many geologists familiar with this general region this formation in part at least is thought to be of Glacial origin. The upper part of the series consists of quartzites (chiefly Lorrain quartzite). As compared with the pre-Huronian, the Cobalt series is little metamorphosed or folded. In most places the Gowganda formation grades up into the Lorrain quartzite, but at some localities there is evidence of an erosion unconformity between the two. This local unconformity may be the result of overlap and probably does not represent a great time-gap.

Both the pre-Huronian and Huronian are intruded by dikes and sills, probably of Keweenawan age. Many different rock-types ranging from norites to aplites are represented and here again the field evidence and relationships make it clear that this diverse petrological variety is due in some cases to original differences in the composition of the magma, in others to assimilation of country rocks, or to magmatic differentiation. Calcite and the association of quartz, chalcopyrite, and silver-cobalt-nickel minerals, which constitute the silver-cobalt veins of the area, are believed to be among the subsidiary differentiates. Primary calcite is found sparingly in the diabase dikes and abundantly in the aplite dikes. In two cases the aplite dikes merge into calcite veins. These sills and dikes and all older rocks of the region are cut by porphyritic olivine diabase dikes.

The numerous gold-quartz veins near West Shiningtree Lake are irregularly mineralized and the gold content is low. In this general region the post-Cobalt diabases have gold-bearing quartz veins associated with them. The gravels along the Vermillion river have been worked for placer gold, but they are rather lean. Small silver-cobalt veins occur at Gowganda. The future commercial importance of the several iron ranges of the area is very doubtful.

J. F. W.

Contributions to the Mineralogy of Black Lake Area, Quebec. By EUGENE POITEVIN and R. P. D. GRAHAM. Canadian Geological Survey, Mus. Bull. No. 27, 1918. Pp. 103, pls. 12, figs. 22.

A detailed study of the minerals of the chromite and asbestos pits in the Black Lake area, Megantic County, Quebec. This is a very productive area, in the serpentine belt of the eastern townships. The country rocks consist of a complex of igneous rocks, ranging from the most

basic to the most acidic in composition, and from late Cambrian to pre-Devonian in age. These igneous rocks probably take the form of thick laccoliths, and the different rock varieties are arranged in the order of decreasing basicity. In many cases erosion has removed the acidic members of the series. Serpentine itself is the least abundant rock of the area, but the most important economically.

Thirty-four mineral species are described from the area. In many cases their origin is given, especially the alumino-silicates rich in lime such as diopside, vesuvianite, and grossularite, which occur as dikes in the peridotite and are not the products of contact metamorphism. The CaO content for these minerals is thought to have been extracted by magmatic waters from the already consolidated portions of the igneous mass. Microscopic diamond crystals were found in the chromite, which is further evidence of the primary origin of chromite. Eleven new forms of diopside are recorded, with a number of illustrative drawings. Colerainite, $H_5Mg_2AlSiO_8$, is a new mineral species found in Coleraine Township, and its physical properties are described in detail with a number of chemical analyses. The mode of origin of the various varieties of serpentine is described with chemical analyses. Good views of the pits and microphotographs are given.

J. F. W.

Report on Braxton and Clay Counties. By RAY V. HENNER. West Virginia Geological Survey, 1917. Pp. 883, pls. 29, figs. 16.

A report on the mineral resources of the area with a discussion of its general geology. Aside from soils the principal wealth of the two counties is in the oil and gas pools, building-stone, and clay and shale for brick. The report is accompanied by topographic and geologic maps.

Part I considers briefly the physiography and history of the development of the region. The counties are in the central part of the state, on the eastern flank of the Appalachian geosyncline. Their present topography is that of a deeply dissected plateau.

Part II is an account of the general geology. The structure is simple, consisting of a gentle dip to the northwest, interrupted by gentle folds. The stratigraphic range is from the upper Devonian through the Paleozoic. Some Pleistocene river terrace deposits are present. A detailed description accompanied by sections is given for each formation present.

Part III discusses the mineral resources, the chief of which are oil and gas. Their development is of recent date. But few wells have been driven into the Chemung, and none below it, the present, known producing horizons being limited to the Pennsylvanian and Mississippian. Coal-mining operations, while on a large scale, are insignificant when compared to those of other counties of the state. The author estimates that the total available tonnage that may eventually be recovered is about 4,440,000,000. While there is not a single brick or pottery plant utilizing clays within the counties, there is an almost inexhaustible supply of raw materials as well as cheap fuel. Sandstone for road macadam and building purposes is abundant. In Clay County about half of the land is unfit for agricultural purposes, and it is suggested that this land be reforested.

Part IV consists of several paleontological contributions. W. A. Pierce presents some notes on the fossils of the Winefrede limestone and Uffington shale in which he notes the absence of a marine fauna. Professor E. C. Case describes the leg bone of a pareiasaurus-like reptile found in the Conemaugh series. I. C. White gives a few notes on the Conemaugh and Permian of the region, and comes to the conclusion that "not only the reptilian life, but also the plant and insect life of the Conemaugh series supports the conclusion that the beginning of red sediments in the Conemaugh marks the dawn of Permian time while there is nothing in the marine life of the epoch to contradict the same when properly interpreted.

Attached to the report is an appendix giving the elevations above mean tide for the area.

A. C. McF.

The Mackenzie River Basin. By CHARLES CAMSELL and WYATT MALCOLM. Canadian Geological Survey, Memoir 108, 1919. Pp. 154, pls. 14, fig. 1, and map.

This is a compilation of what is known concerning the geology of the Mackenzie River basin, which is about 1,350 miles long and 100 miles wide at the mouth of the river and 900 miles wide near the center, with a total area of about 682,000 square miles.

Parts of three chief physiographic provinces are included in this area and each one runs almost the whole length of the basin. They are the Laurentian Plateau on the east, the Great Central Plain of North America in the center, and the Cordilleran region on the west.

The outstanding characteristics of each of these three provinces is given along with a description of the Mackenzie River, including its lakes and larger branches.

Early pre-Cambrian rocks outcrop in the eastern part of the basin and consist of various schists, slates, limestones, and quartzites intruded by granites and gneisses. These are overlaid unconformably by sandstones, limestones, and basic flows and intrusives of late pre-Cambrian age. The Paleozoic is represented by a series of limestones, shales, and sandstones, not subdivided and of unknown age. A series of limestones and shales is classed as the Devonian, but the basal part is Upper Silurian in age, according to fossil evidence. Beds of gypsum are interbedded with these basal limestones, and the strata above the gypsum beds are fractured and folded, which is thought to be the result of expansion due to the alteration of beds of anhydrite to gypsum. The Mesezoic is represented by the Cretaceous sandstones and shales which occupy nearly the whole of the valleys of Athabasca and Peace rivers. Traced northward from Peace River these formations show three changes: a decrease in thickness, replacement of sandstone by shale, and a substitution of subaerial for marine conditions of deposition. In the sandstones in the basin of Athabasca River there are a number of workable seams of coal as well as extensive deposits of bituminous sands. A few small areas of Tertiary sands and clays overlie the Cretaceous with slight unconformity. Lignite seams occur in these beds.

Only the highest parts of the Rocky and Mackenzie mountains escaped Pleistocene glaciation. The ice from the Keewatin Glacier, which moved north, west, and south, entered this area, as well as ice from the mountains to the west. Glacial and lacustrine deposits are very extensive.

Descriptions are given of the bituminuous sands, with a discussion of their possible utilization, also notes on the various coal horizons, gypsum beds, salt springs, and clays of the area. Cobalt, gold, hematite, lead, zinc, and nickel are known to exist but very little is known as to their extent. A gas-bearing horizon in the Cretaceous has been known for twenty years, also petroleum from borings on the Peace River. During the last two years, active prospecting for gas and oil has been carried on with favorable results.

This is a valuable compilation and contribution to the geology of this little-known region. In the future it will serve as the starting-point for geologists working there. A good bibliography is given.

J. F. W.

Report on Berkeley, Morgan and Jefferson Counties. By G. P. GRIMSLEY. West Virginia Geological Survey, 1916. Pp. 644, pls. 37, figs. 20.

This report covers an area of 768 square miles, comprising what is known as the "Eastern Panhandle," and is accompanied by topographic and geologic maps.

Part I is concerned with the physiography, climate and industrial development of the area.

Part II deals with the general geology. The structure is that typically developed in the Appalachians, consisting of parallel folds and faults. The deformation is not intense. Stratigraphically the rocks range from the Algonkian through the Carboniferous. Detailed and generalized sections, with local faunal lists, are given. Questions of correlation are discussed, and attention is given to the origin of the Catskill formation which is well developed in the region.

Part III is a discussion of the mineral resources, the more important of which include glass-sand, limestone clays, and road materials. There is included with each a discussion of the preparation and uses of the raw material.

As a result of the vast deposits of Cambro-Ordovician limestones, the limestone and lime industries are well developed. The Stones River formation contains limestone of great purity, and furnishes a high-grade fluxing material and a high-grade lime. An abundant supply of clay and shale for brick is available, the Martinsburg shale being of importance. Sandstone, quartzite, and limestone for road metal are found in abundance. Iron ore is of negligible importance but the region is admirably situated with respect to transportation, coal production and limestone fluxes, for the steel industry.

Attached to the report are two appendixes: (*a*) levels above the tide in the Eastern Panhandle region; (*b*) location of true meridian lines in the Eastern Panhandle region.

A. C. McF.